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Benchmarking Measures for the Adaptation of New Irrigation Solutions for Small Farms in Egypt

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Abstract: The aim of this study is to construct and validate an expert system to predict the adaptation of irrigation technologies, water-saving strategies, and monitoring tools by small-scale farmers in Egypt. The research investigates the impact of economic, educational, environmental, and social factors on adaptation rates. To build the expert system, extensive knowledge was collected from experts, key concepts were identified, and production rules were created to generate tailored scenarios. These scenarios utilize the empirical cumulative distribution function (ECDF), selecting the scenario with the highest ECDF as the optimal irrigation technology. This approach ensures well-informed, data-driven decisions that are tailored to specific conditions. The expert system was evaluated under the conditions of ten small farms in Egypt. The results indicate that water cost and availability are significant drivers of technology adaptation. Specifically, subsurface drip irrigation (SDI) demonstrated an adaptation percentage of 75% at high water costs, with probabilities of 0.67 and 0.33, while soil mulching (SM) showed a 75% adaptation rate with a probability of 0.33 in high-cost scenarios. Conversely, when water availability was high, the adaptation percentage for all techniques was zero, but it reached 100% adaptation with a probability of 0.76 for SM and SDI and a probability of 1 for variable number of drippers (VND) and the use of sensors as monitoring tools during water shortages. Educational attainment and professional networks enhance the adaptation of advanced technologies and monitoring tools, emphasizing the role of knowledge and community engagement. Environmental conditions, including soil texture and salinity levels, directly affect the choice of irrigation methods and water-saving practices, highlighting the need for localized solutions. The source of irrigation water, whether groundwater or surface water, influences the preference for water-saving technologies. The study underscores the importance of tailored approaches to address the challenges and opportunities faced by small farmers in Egypt, promoting sustainable agriculture and efficient water management. The evaluation findings reveal that SDI is the most favored irrigation technology, with a probability of 0.55, followed by variable number of drippers (VND) at 0.38 and ultralow drip irrigation (ULDI) at 0.07 across various scenarios for small farmers. Regulated deficit irrigation (RDI) and SM are equally preferred water-saving strategies, each with a probability of 0.50. Sensors emerged as the preferred monitoring tool, boasting a high probability of 0.94. The analysis reveals the critical roles of economic pressures, educational levels, environmental conditions, and social networks in shaping the adaptation of sustainable agricultural practices.

Keywords: benchmarking; irrigation technologies; small-scale farmers; water-saving strategies; monitoring tools

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1. Introduction

The adaptation of new irrigation techniques is usually refused by farmers for many reasons, such as the complexity, the cost, and less expertise of this new technique and other elements related to the social and economic. The providers utilize a measure of profitability as the key whole-farm performance indicator [1].

Benchmarking can be the best selection for determining the best irrigation techniques, water-saving strategies, and monitoring tools. Benchmark is defined as a standard against which something can be assessed or measured [2,3]. Benchmarking for irrigation solutions is crucial in order to evaluate the effectiveness and efficiency of new irrigation technologies and practices [4,5].

Additionally, benchmarking allows for the identification of best practices and areas for improvement, ultimately leading to sustainable and impactful irrigation solutions [4,6].

The scarcity of water in Egypt is constantly increasing; the current annual amount of water is not sufficient to meet the needs of the growing population and expanding agricultural and industrial sectors. The river Nile, which is the primary source of water for Egypt, is under immense pressure due to factors such as climate change and inefficient water management practices [7–10].

The adaptation of new irrigation techniques is crucial for improving crop yield and water efficiency in agriculture, especially in regions with limited water resources like Egypt [11,12]. In recent years, there has been a growing emphasis on sustainable and efficient irrigation methods to address water scarcity and maximize agricultural productivity [13–15]. Ref. [14] reported that benchmarking aims to analyze the effectiveness of various irrigation techniques and their potential for adaptation in agricultural practices. By evaluating different methods and their impact on crop yield, water usage, and environmental sustainability, this report will provide valuable insights for farmers and agricultural stakeholders seeking to enhance their irrigation practices [16].

The social and economic elements that affect the adaptation of new irrigation technologies have not yet been studied. Many researchers and decision makers take into consideration the technical elements related to technology, and few others consider the social elements of the adaptation of new irrigation solutions [17]. Also, some consider it a valuable tool that has proven itself in the business and commercial sector [4]. Benchmarking in irrigation is a more complex task than in many other sectors [4].

The analysis of so many factors or benchmarks requires approbative methods or tools. An expert system is a computer program or information system, and one of the most applicable artificial intelligence (AI) programs could do this carefully [18–20].

Currently, there is a gap between scientific knowledge and irrigation practices used by the small farmers that should be addressed to conciliate the feasibility of agribusiness by optimizing water use. Benchmarking has been proposed as a tool to drive performance improvement in the irrigation and drainage sector [21]. This study, which will focus on small farmers, is conceived primarily as a technology adaptation and technology transfer, where established know-how, with some further development of low-cost devices and refinements of water-saving practices, will be translated into an easy language for the end users in order to guarantee its final use by small farmers.

2. Materials and Methods

Irrigation Techniques, Water-Saving Strategies, and Monitoring Tools.

There are many irrigation techniques; we selected the three most common techniques: variable number of drippers (VND), ultralow-drip irrigation (ULDI), and subsurface drip irrigation (SDI). Two water-saving strategies were selected: soil mulching (SM) and regulated deficit irrigation (RDI). RDI is an irrigation strategy that involves adopting a moderate reduction in irrigation water only when the crop is less sensitive to water stress (phenological phases). Three soil water content monitoring tools were used: meteorological weather station (MTS), sensors, and thermal images.

Benchmarking for selecting the appropriate irrigation solution.

Selecting the appropriate irrigation technologies and practices in the current state and in simulated scenarios. The benchmarking elements of selecting the appropriate new irrigation solutions are determined and selected from the main technical, social, and economic elements. The benchmarking that was used in this study is listed as follows:

- Farm area: this study was interested in small farms < 2 ha.
- Region: the study was one only in Egypt.
- Joining a professional organization: its values were yes (if farmer joining a professional organization) or no.
- Crop has two properties: (1) crop type: two different crops olive and citrus have been selected; (2) the mean income of growing the crop.
- Profit/cost has two properties: (1) cost of water, its values low, medium, and high; (2) cost of technology or practice, its values low, medium, and high.
- People have three properties: (1) awareness of farmer by technology or practice, its values low, medium, and high: (2) irrigation expertise in managing farms, its values low, medium, and high; (3) instruction level, its values: none—primary—secondary—baccalaureate—university and other.
- Soil has only one property: soil texture, its values light, medium, and clay.
- Irrigation water has four properties: (1) sources, its values groundwater—surface water—alternative water sources (i.e., wastewater, salt water); (2) salinity level: low, moderate, and high; (3) irrigation water availability, its values available, medium, and shortage; (4) irrigation system type its values surface irrigation and drip irrigation.
- The social, environmental, and economic factors that most influence the selection of appropriate irrigation strategies have been quantified and scaled from 0 to 1, with the scale divided into five values (0, 0.25, 0.50, 0.75, and 1). A value of zero indicates that the probability of adopting a particular technique or strategy is zero, while a value of 1 indicates the highest probability of adaptation, meaning that 100% of farmers would adopt this technique or strategy. These benchmarking factors were utilized to design questionnaires, which were then administered to three Egyptian experts in water management to gather their insights. These benchmarking factors were used to create questionnaire forms, which were utilized to ask and gather information from three Egyptian experts in water management.

2.1. Building the Expert System

The selected elements have been analyzed by using expert system techniques.

An expert system was built to support the decision maker or farmers by the sound decision for selecting the best scenario for irrigation technology, water saving, and monitoring or observation methods (Figure 1).

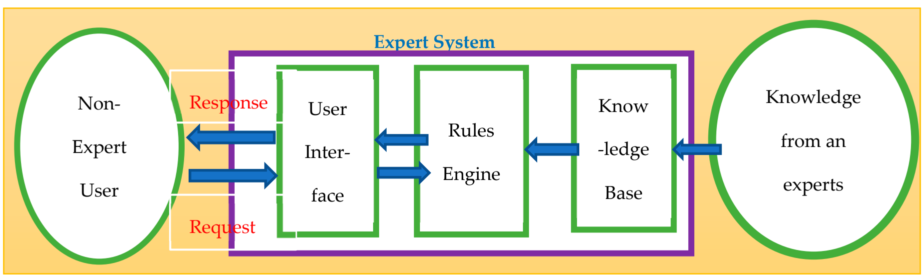

Figure 1. The expert system components.

An expert system (ES) is a computer program designed to emulate the logic and reasoning process that an expert would use to solve a problem in their field of expertise by using artificial intelligence technology [22]. It performs many functions as an expert does, such as posing relevant questions and explaining its reasoning process.

The stages of building the ES: identification of the problem, conceptualization, formalization, implementation, verification and validation, and evaluation of ES, as shown in Figure 2. This methodology represents an attempt by experienced knowledge engineers to characterize the complex process that takes place during the development process. Also, these stages are highly interrelated and interdependent (Figure 2).

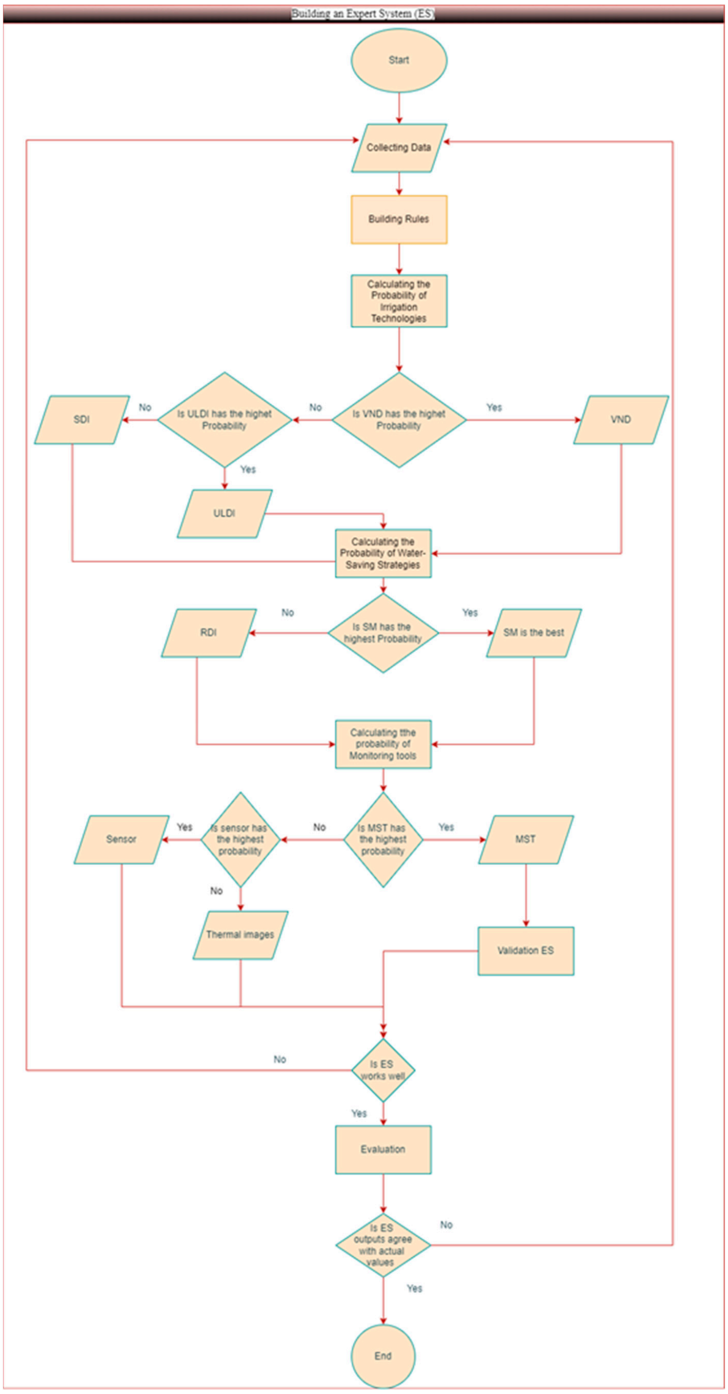

Figure 2. Flowchart for the process of building and evaluation of the expert system.

2.1.1. Identification of the Problem

The problem that the expert system will solve is to select the best irrigation technology, water-saving strategy, and monitoring or observation tool or method for irrigation management.

2.1.2. Conceptualization

In this stage, the most important criteria or concepts are selected that affect the selection of the best scenario for water management from many meetings with the farmers and non-farmers to get the main concept and knowledge that are used for building ES. The main concepts are farm; region joining a professional organization; crop; and people; they are shown in Table 1 and its properties, values, and type of values.

Table 1. The concepts or benchmarking measures for the adaptation of new irrigation solutions.

Concepts/Factors	Properties	Value	Type of Value
Economic Factors			
Water	Cost of water	Low, medium, and high	String (text)
Water	Irrigation water availability	Available, medium, and shortage	String (text)
Cost	Income of small farm	Low, medium, and high	String (text)
Cost	Cost of technology or practice	Low, medium, and high	String (text)
Educational and Social Factors			
Pepole	Instruction level/level of education	None—primary—secondary—baccalaureate—university other	String (text)
Pepole	Joining a professional organization	Yes—no	Boolean
Pepole	Awareness of farmer	Low, medium, and high	String (text)
Pepole	Irrigation expertise in managing farms	Low, medium, and high	String (text)
Environmental Factors			
Soil	Soil texture characteristics	Light, medium, and clay	String (text)
Water	Salinity level	Low, moderate, and high	String (text)
Water	Sources	Groundwater—surface water—alternative water sources (i.e., wastewater, salt water	String (text)
Water	Irrigation system type	Surface irrigation, drip irrigation	String (text)
Crop	Type	Citrus and olive	String (text)
Farm	Area	0–2 ha	Constant
Region		Egypt	String (text)

2.1.3. Formalization

Formulation involves characterizing the variables, the key factors, and qualifiers for irrigation management under diverse farm situations and conditions. Therefore, this procedure involves the representation of the variables, key factors, and qualifiers into the production rules that make it usable within the development environment of the construction of the expert system rule-based program. The easiest and best way to represent knowledge and data analysis is the development of knowledge and data as rules.

Probability of selecting the best irrigation practice.

The method for estimating the probability of selecting the best irrigation practice based on expert opinions:

Expert Input: Gather opinions from a panel of experts regarding different irrigation practices, including technologies, water-saving strategies, and monitoring tools.

Probability Determination: Calculate the probability of each scenario being the best option by considering the distribution of expert opinions. This is carried out by dividing 1 by the number of unique opinions provided by the experts.

Empirical Cumulative Distribution Function (ECDF): For each factor or concept (e.g., a specific irrigation technology), construct an ECDF, denoted as $S_n(x)$, using the following rule:

$$S_n(x) = \begin{cases} 0, \ x < x_{(1)} \\ \frac{k}{n}, \ x_{(k)} \leq x < x_{(k+1)} \ , k = 1, 2, \ldots\ldots, n \\ 1, \ x \geq x_{(n)} \end{cases} \quad (1)$$

- If x is less than the smallest observed value $x_{(1)}$, then $S_n(x) = 0$.
- For values of x between the k and (k + 1) ordered observations, $S_n(x) = \frac{k}{n}$, where n is the total number of observations (in this case, the number of experts).
- If x is greater than or equal to the largest observed value $x_{(n)}$, then $S_n(x) = 1$

Averaging Probabilities: Compute the average probability for each factor or concept by summing the individual probabilities $S_{i.}(x)$ and dividing by the total number of factors nf, denoted as $S_{av.}(x)$:

$$S_{av.}(x) = \sum_i^n S_i(x)/nf \quad (2)$$

Selection Criteria: The best irrigation practice for each category (technology, water-saving strategy, monitoring tool) is identified as the one with the highest average probability $S_{av.}(x)$. To encompass all possible scenario conditions, 191,318,760 roles were built.

Implementation and verifying and validation.

After completing building the expert system, the next stage is to test and compare the predicted values of the expert system with the actual values. The program runs 100 times for different 10 small farmers situations. Figure 3 shows the input of information, which plays a key role in the modeling and optimization of technologies.

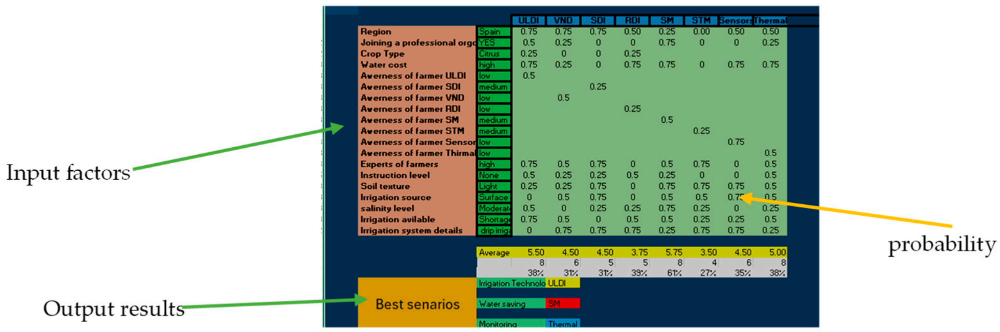

Figure 3. The user interface and output of the expert system.

3. Results

3.1. Economic Factors

3.1.1. Water Cost

The results showed the effects of water cost on the selection of the best irrigation scenarios of irrigation technologies, water-saving strategies, and monitoring tools, as shown in Figure 4.

The results showed that if the cost of water ranged from low to medium, the adaptation of irrigation technology and monitoring tools did not increase by 50%. With the increase in water cost, the adaptation percentage reached 75%, and the best probability was 0.33 for VND and SDI; the best probability for water-saving strategies and monitoring tools was 0.67 for soil mulching and soil sensors.

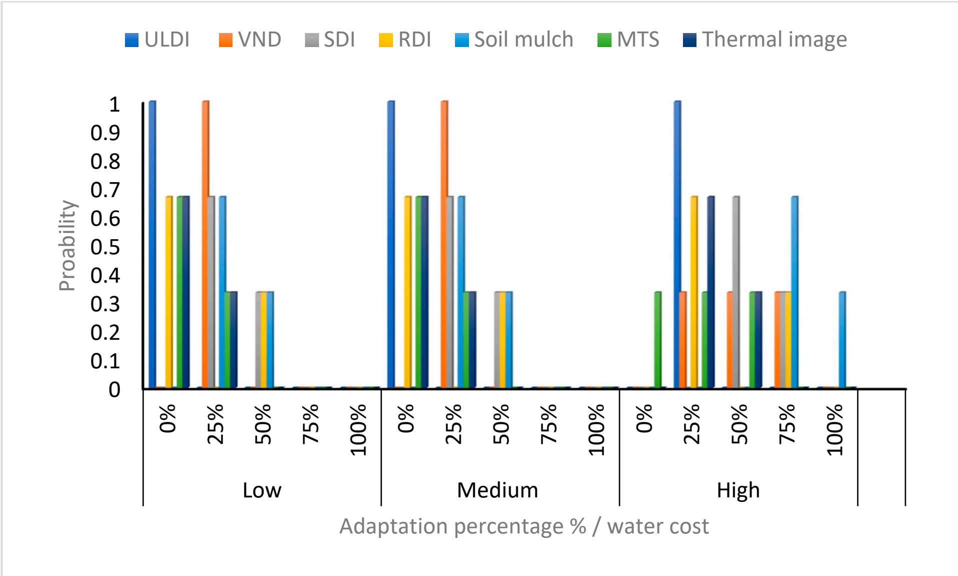

Figure 4. The probability values of irrigation technology, water-saving strategies, and monitoring tools under water cost concept.

3.1.2. Water Availability

The impact of water availability on small farmers' choices regarding irrigation technologies, water-saving strategies, and monitoring tools is illustrated in Figure 5.

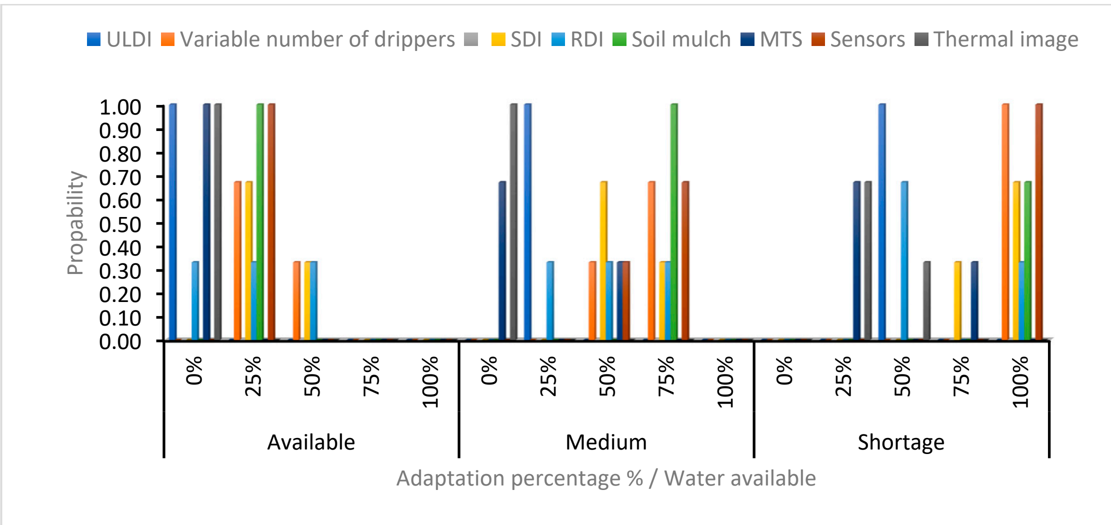

Figure 5. The probability values of irrigation technology, water-saving strategies, and monitoring tools under water availability concept.

When water was plentiful, the rate at which irrigation technologies was adopted did not surpass 50%. However, as water availability decreased to a medium level, the adaptation rate climbed to 75%. In situations of even greater water scarcity, the adaptation rate peaked at 100%.

The likelihood of adopting variable number of drippers (VND) technology was greatest, with probabilities of 0.67 and 1, under conditions of medium and low water availability, respectively. Similarly, soil mulching showed high adaptation probabilities of 1 and 0.67, corresponding to 75% and 100% adaptation rates under medium and low water availability, respectively.

In terms of monitoring tools, sensors were the most preferred, with adaptation probabilities of 0.67 and 1 under medium and low water availability, respectively.

3.2. Educational and Social Factors

3.2.1. Instruction Level

The probability and adaptation percentage of different scenarios of irrigation technologies, water-saving, and monitoring tools are shown in Figure 6.

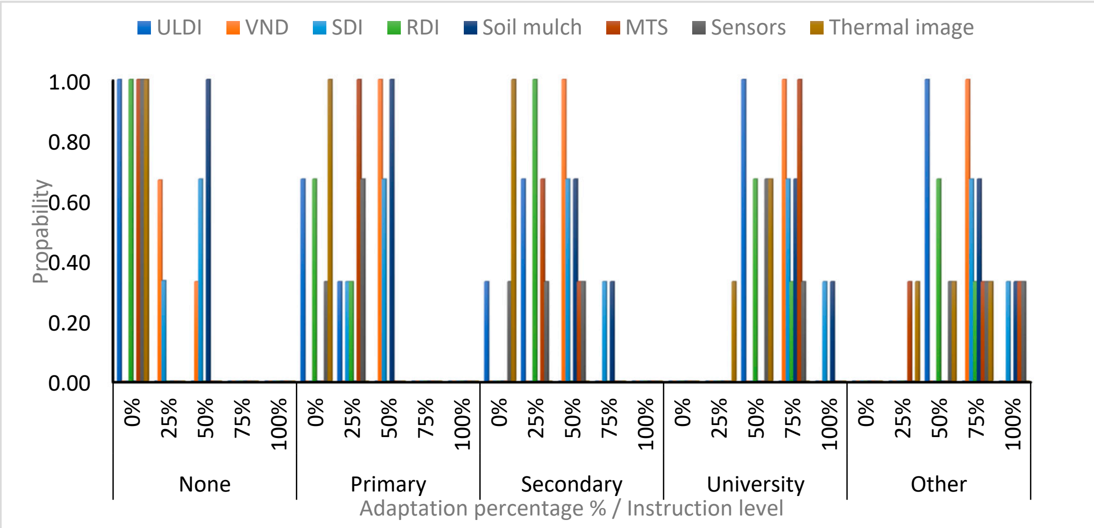

Figure 6. The probability values of irrigation technology, water-saving, and monitoring tools under instruction level concept.

With the increase in the instruction level from none to university, the probability and adaptation of the different scenarios increased. The adaptation percentage did not increase more than 50% from one to primary level. At the secondary level, the probability arrived at 75% by probability 0.33 for SDI and soil mulching. At the university level, the adaptation percentage reached 100% by probability 0.33 for SDI and soil mulching also.

3.2.2. Joining a Professional Organization

The probability of the selection and the percentage of adaptation of irrigation technologies, water-saving strategies, and monitoring tools under two situations (when a farmer is joining a professional organization or not) are shown in Figure 7.

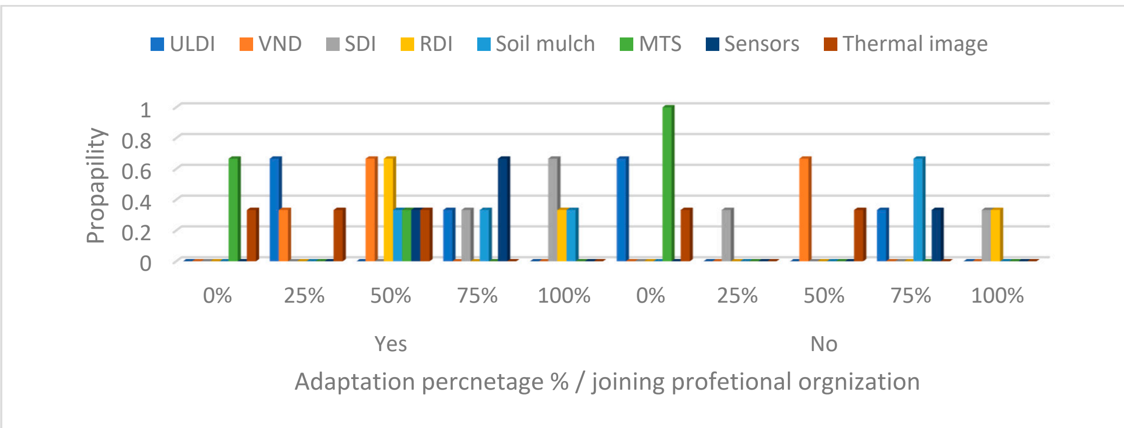

Figure 7. The probability values of irrigation technology, water-saving strategies, and monitoring tools under joining a professional organization concept or not.

The results show the effects of two situations: the first is the farmer joining a professional organization, and the second is the farmer not joining.

The probability of selecting the irrigation technologies, water-saving strategies, and monitoring tools ranges from 0.33 to 1, and the adaptation percentage ranges from 0% to 100%.

The results showed that the highest probability with high adaptation (100%) of irrigation technology was 0.67 and 0.33 for SDI under two situations, respectively. ULDI has a low opportunity of adaptation by probability 0.67 at the second situation.

The opportunity of selecting one of two water-saving strategies (RDI and soil mulching) was equal in many instances. The prediction was in favor of soil mulching at adaptation percentage 75%, and the highest probability of selecting the best water-saving strategy was 0.67 in the second situation.

Soil sensors were the best selection by probability 0.67 and 0.33 for two situations, respectively.

3.2.3. Awareness of Small Farmers by the Techniques

The results of the effect of awareness of small farmers by the different irrigation techniques (irrigation technology, water-saving strategies, and monitoring tools) are being clarified in Figure 8.

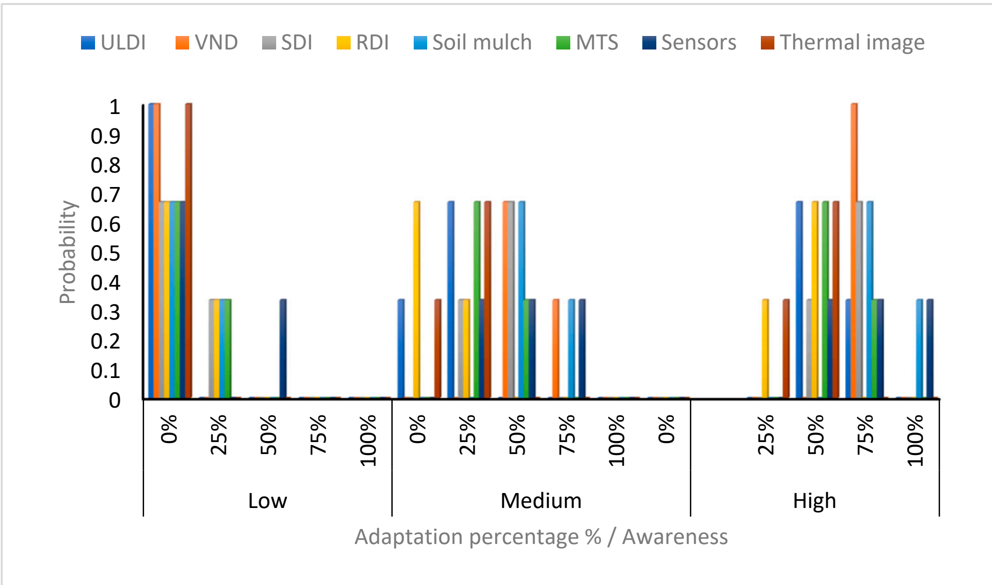

Figure 8. The probability values of irrigation technology, water-saving strategies, and monitoring tools under awareness of farmers by the irrigation technologies concept.

The results showed the fact that the increase in awareness by using technology will increase the probability and adaptation percentage. If the awareness of farmers is low, the adaptation percentage does not increase to more than 25% for all techniques except the use of soil sensors in monitoring the soil water content, which will reach 50% by probability 0.33. With the increase in the awareness of farmers, the adaptation reached 75% and 100% for medium and high, awareness respectively, by probability 0.33 for soil mulching as the best water-saving strategy and soil sensors as the best monitoring tools.

3.2.4. Expertise of Small Farmers of Irrigation Management

The relationship among the expertise of farmers and the probability of the adaptation of the different techniques is shown in Figure 9.

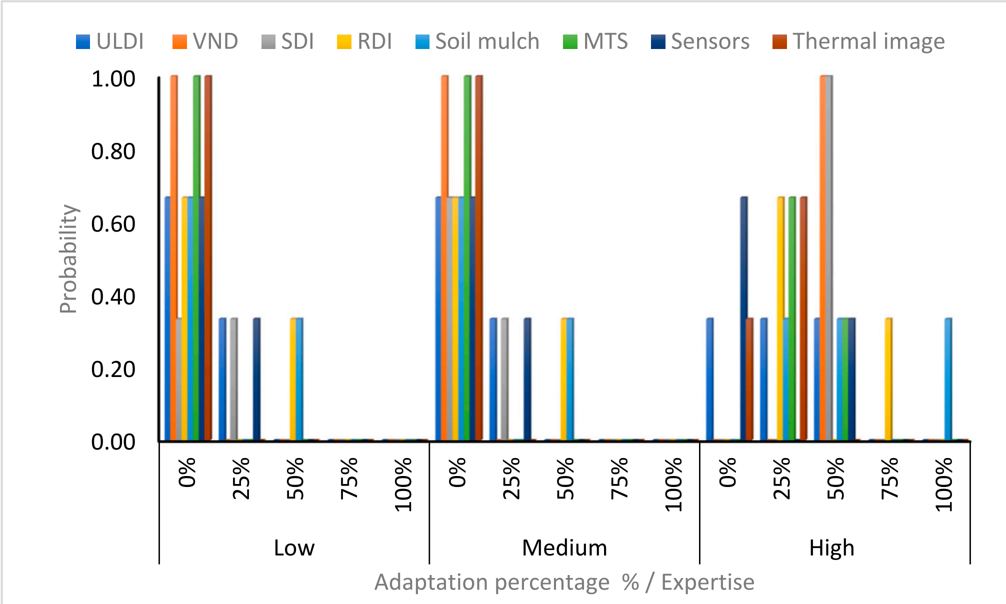

Figure 9. The probability values of irrigation technology, water-saving strategies, and monitoring tools under expertise of small farmers of irrigation management concept.

The results showed that the adaptation percentage and probability increased according to the expertise of farmers. The adaptation percentage did not increase by more than 50% as the probability was 0.33 for RDI and soil mulching under low and medium expertise. When the expertise arrived at high expertise, the change in adaptation percentage and probability reached 75% and 100% by 0.33 probability for RDI and soil mulching, respectively.

3.3. Environmental Factors

3.3.1. Soil Texture

The soil texture affected the selection of the best scenarios as shown in Figure 10.

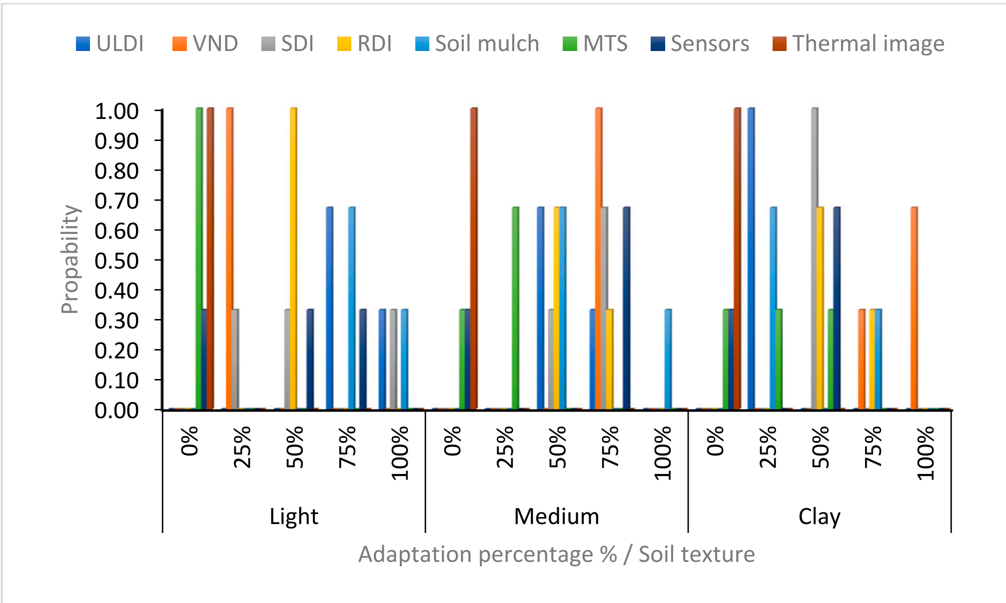

Figure 10. The probability values of irrigation technology, water-saving strategies, and monitoring tools under soil texture concept.

The results showed that the best predicted scenario in light soil was the use of ULDI or SDI for irrigation technology, soil mulching for water saving, and sensors for monitoring soil water content at adaptation percentage 100% and probability 0.33. In medium soil texture, the best scenario was the use of VND or SDI at adaptation 75% and probability 1 and 0.67, respectively; also, the use of soil mulching and soil sensors at adaptation and probability 100% and 75% at 0.33 and 0.67, respectively. The best predicted scenario in clay soil was using VND, RDI, or soil mulching and sensors at adaptation percentages 100%, 75%, and 75% by probability 0.67, 0.33, and 0.33, respectively.

3.3.2. Salinity Level

The effects of water salinity level on the selection of the best scenarios are shown in Figure 11.

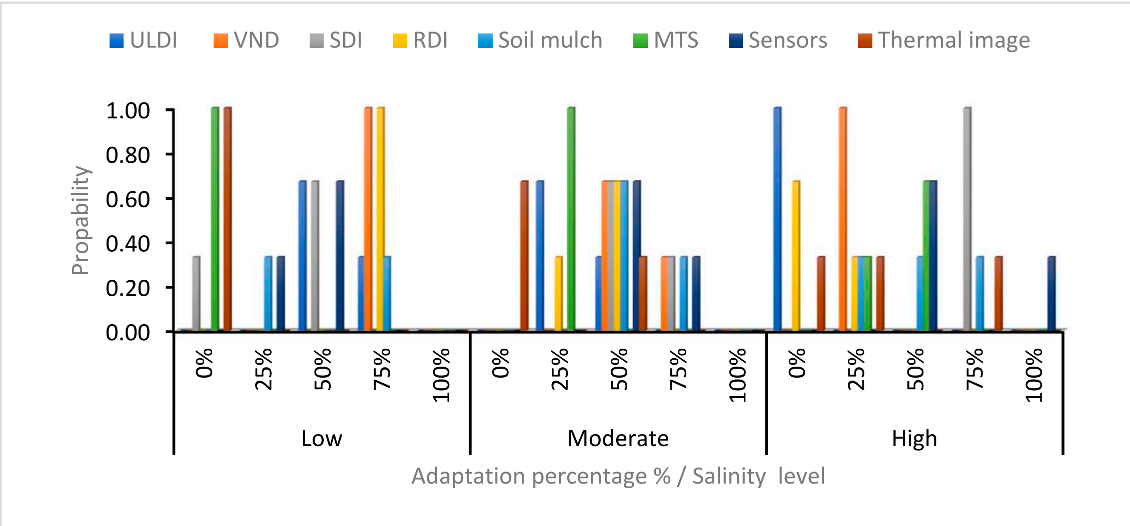

Figure 11. The probability values of irrigation technology, water-saving strategies, and monitoring tools under salinity level concept.

With the increase in water salinity, the adaptation and probability decreased. The maximum value of adaptation percentage with irrigation technologies was 75% and probability 1, 0.33, and 1 for VND, SDI, or VND and SDI at low, moderate, and high salinity levels, respectively. The maximum values of probability for selecting water-saving strategies were 1, 0.33, and 0.33 for RDI, soil mulching, and soil mulching at low, moderate, and high salinity levels, respectively. Monitoring tools have been recommended when the level of water salinity reaches moderate and increased to a high level, the probability 0.33 and adaptation percentage 75% and 100%, respectively.

3.3.3. Source of Water

The source of water effects on the probability and adaptation of the best scenarios is shown in Figure 12.

The best predicted scenarios when the source of water was groundwater were VND, soil mulching, and sensors for monitoring the soil water content at adaptation percentage 50% and probability 0.33. Under surface water, the best scenarios were VND, soil mulching, and sensors at adaptation percentage 50% and probability 1, 1, and 0.33, respectively. Alternative sources of water direct the ability of water in the direction of not selecting any irrigation technology and water-saving strategies, but it recommended using sensors for monitoring soil water content by adaptation percentage 50% and probability 0.33.

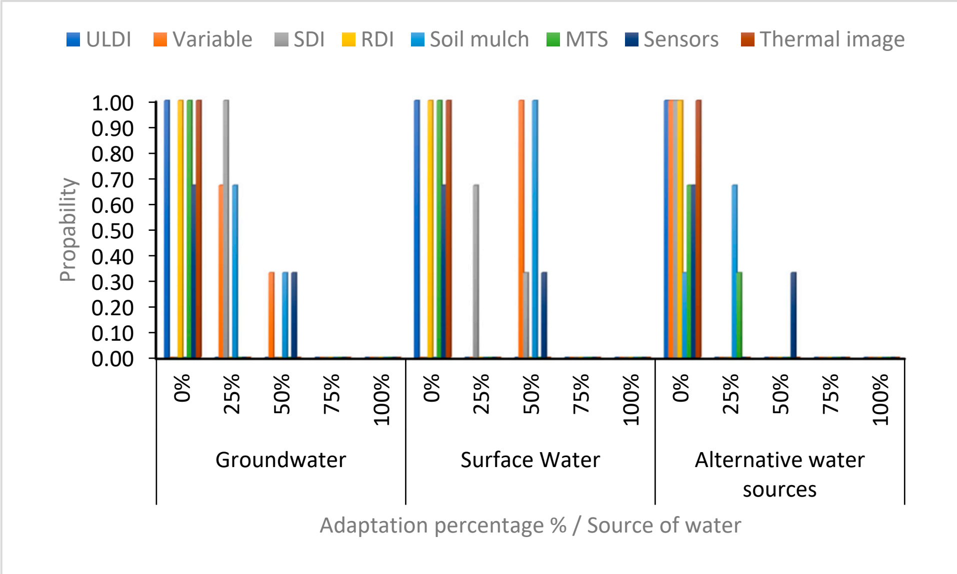

Figure 12. The probability values of irrigation technology, water-saving strategies, and monitoring tools under source of water concept.

3.3.4. Irrigation System

The findings depicted in Figure 13 illustrate the impact of irrigation system types on the adaptation of various irrigation technologies. The drip irrigation system emerged as the most favored, surpassing surface irrigation in terms of adaptation rates. Specifically, drip irrigation exhibited a higher likelihood of being adopted, with a probability of 1, compared to surface irrigation, which had a probability of 0.33. Neither system exceeded a 75% adaptation rate. Within the category of drip irrigation, variable number of dripper (VND) and subsurface drip irrigation (SDI) stood out as the most effective technologies, both showing a 100% probability of selection and a 75% adaptation rate. Furthermore, soil mulching was identified as the most effective water-saving strategy for both drip and surface irrigation systems, with an adaptation rate of 75% and probabilities of 1 for drip irrigation and 0.33 for surface irrigation.

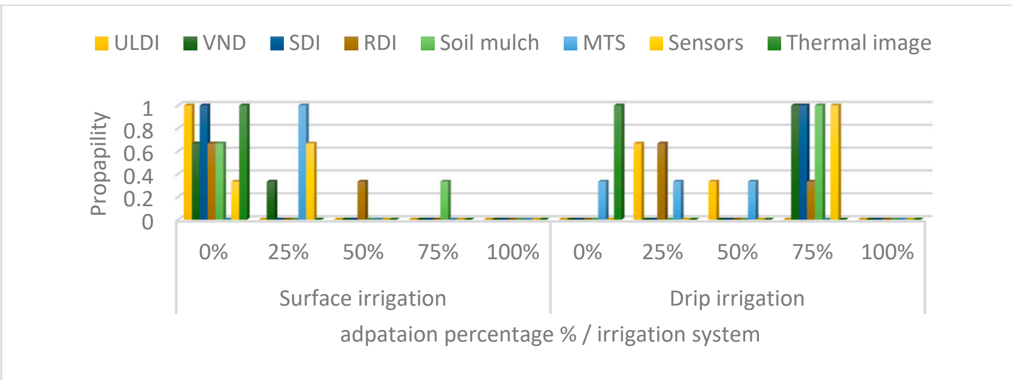

Figure 13. The probability values of irrigation technology, water-saving strategies, and monitoring tools under irrigation system concept.

3.3.5. Crop Type

Two crop types (citrus and olive) have been selected to check the effect of crop type. The results have been clarified in Figure 14.

The results showed that the selection among the different irrigation techniques was direct to ULDI and SDI for citrus and olive, while VND. The soil mulching has probability 1 at adaptation percentage 75% and 50% in the first and second situations. The meteorological station (MTS) and soil sensors were the best selection for monitoring the water in the soil by probability 0.33 at 50% adaptation percentage in the two situations.

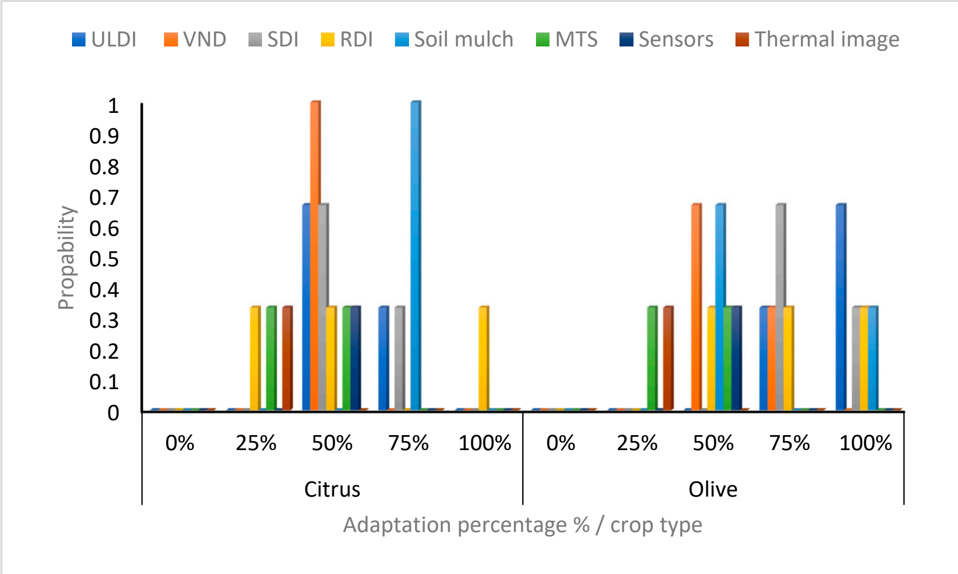

Figure 14. The probability values of irrigation technology, water-saving strategies, and monitoring tools under crop type concept.

3.3.6. Farm Area

Farm area in this study is the small farms, which area < 2 ha. The values of the probability were equal, which means it is not effective in the selection of the best scenario as shown in Table 2.

Table 2. The probability table of irrigation technology, water-saving strategies, and monitoring tools under farm concept.

Concept	Value	Irrigation Technologies			Water-Saving Strategies		Monitoring Tools		
		ULDI	VND	SDI	RDI	SM	MTS	Sensors	Thermal
Farm/Area	0–2 ha	1/3	1/3	1/3	1/2	1/2	1/3	1/3	1/3

Note(s): Where VND = variable number of drippers, SM = soil mulch, MTS = metrological station, and Thermal = thermal image.

3.3.7. Region

The region is one of the affected elements for selecting the best scenario, but in this study, it is concentrated in Egypt only as a case study, and all experts were Egyptians. The values of probability for the region were also equal and had no effect on the selection of the scenarios as shown in Table 3.

Implementation and verifying and validation.

After completing the construction of the expert system, the subsequent phase involves testing and comparing the predicted values generated by the expert system with the actual values. The program was run one hundred times for ten different small farmer conditions, and the input and outcomes of the model are presented in Table 4.

Table 3. The probability values table of irrigation technology, water-saving strategies, and monitoring tools under region concept.

Concept	Value	Percentage of Adaptation (%)	Irrigation Technologies			Water-Saving Strategies		Monitoring Tools		
			ULDI	VNOD	SDI	RDI	SM	MTS	Sensors	Thermal
Region	Egypt	0	1	0	0	0	0	1	1/3	2/3
		25%	0	1	0	0	0	0	0	1/3
		50%	0	0	1/3	2/3	0	0	2/3	0
		75%	0	0	2/3	1/3	1	0	0	0
		100%	0	0	0	0	0	0	0	0

Table 4 reveals significant insights into the average probabilities associated with distinct categories such as irrigation technologies, water-saving strategies, and monitoring tools. Subsurface drip irrigation (SDI) emerges as the most favored irrigation technology with a substantial probability of 0.55, surpassing variable number of drippers (VND) at 0.38 and ultralow drip irrigation (ULDI) at 0.07, leading to an average probability of (0.33 ± 0.203) for irrigation technologies. In the realm of water-saving strategies, both regulated deficit irrigation (RDI) and soil mulching (SM) shine with an equally strong probability of 0.50 each, culminating in an average probability of 0.50 for this category. Among monitoring tools, sensors notably stand out with a high probability of 0.94, contrasting with meteorological station (MST) at 0.06 and thermal imaging at 0.00, resulting in an average probability of (0.33 ± 0.38). These findings highlight the varying levels of preference or efficacy within each category, underscoring the prominence of SDI, sensors, and RDI as favored choices in their respective domains.

Exploring the nuances and potential underlying reasons for the observed probabilities of adopting different irrigation technologies, water-saving strategies, and monitoring tools among small farmers in Egypt. This analysis will consider the interplay between various factors, including economic, educational, environmental, and social aspects, to offer a more comprehensive understanding of the dynamics at play.

Detailed analysis of factors influencing adaptation rates.

3.3.8. Economic Factors

- Water Cost: The table indicates that farmers facing high water costs (Cases 3, 7, 8) are more likely to adopt water-saving irrigation technologies such as SDI and ULDI. This is particularly evident in Case 3, where the high-water cost coincides with a 58% probability of adopting SDI and a 9% probability of adopting ULDI. This suggests that economic pressures can drive technological adaptation for cost savings.
- Irrigation Water Availability: The availability of irrigation water also plays a crucial role. In cases of shortage (Case 3), there is a higher probability of adopting water-saving strategies like RDI (56%) and SM (44%), indicating that scarcity can be a strong motivator for adopting conservation measures.

Table 4. The adaptation percentage of the different irrigation technologies, water-saving strategies, and monitoring tools under different situations of small farmers.

Concepts	**Case Number**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Economic Factors										
Water cost	Low	Low	High	Medium	Medium	Medium	High	High	Medium	Medium
Irrigation available	Medium	Medium	Shortage	Available	Medium	Medium	Medium	Medium	Available	Medium
Educational and Social Factors										
Instruction level	Primary	University	Secondary	University	None	Secondary	Secondary	Secondary	None	University
Joining a professional organization	NO	NO	YES	NO	NO	YES	NO	NO	NO	YES
Awareness of farmer ULDI	Medium	Medium	Low	Low	Low	Low	Low	Low	Low	Low
Awareness of farmer SDI	Low	Low	Medium	Low	Low	Low	Medium	Medium	Medium	Medium
Awareness of farmer VND	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Awareness of farmer RDI	High	Medium	Medium	Low	Low	Low	Low	Low	Low	Low
Awareness of farmer SM	Medium	Medium	High	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Awareness of farmer MST	Medium	Low	Medium	Low	Low	Low	Low	Low	Low	Low
Awareness of farmer Sensors	Low	Low	Low	Medium	Medium	Medium	Low	Low	Low	Low
Awareness of farmer Thermal	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Experts of farmers	High	Medium	High	High	Medium	Medium	Medium	Medium	Low	High
Environmental Factors										
Soil texture	Medium	Medium	Light	Light	Light	Light	clay	clay	Light	Light
Salinity level	Low	Low	Low	Low	Low	Low	Low	Low	Moderate	Moderate
Irrigation source	Surface Water	Surface Water	Surface Water	Groundwater	Surface Water	Surface Water	Groundwater	Groundwater	Groundwater	Surface Water
Irrigation system type					drip irrigation					
Crop Type			Citrus					Olive		
Region					Egypt					
Probability of Irrigation Technology										
VND	37	33	33	42	43	31	40	49	44	30
SDI	52	60	58	52	48	62	51	45	56	65
ULDI	11	7	9	6	9	7	9	6	0	5
Probability of Water saving										
SM	56	55	44	51	59	47	48	38	59	52
RDI	44	45	56	49	41	53	52	62	41	48
Probability of Monitoring Tools										
MST	8	5	16	1	1	8	9	5	0	7
Sensors	91	95	84	98	99	92	90	95	100	92
Thermal	1	0	0	1	0	0	1	0	0	1
Actual selection										
Irrigation technology	VND	VND	VND	SDI	SDI	SDI	VND	SDI	SDI	SDI
Water-saving strategies	SM	SM	SM	RDI	SM	SM	SM	RDI	SM	SM
Monitoring tools	Other	Other	Other	Sensors	Other	Other	Other	Sensors	Sensors	Other

3.3.9. Educational and Social Factors

- Instruction Level and Professional Organizations: The data show that farmers with higher education levels (Cases 2, 10) and those who are members of professional organizations (Cases 3, 6, 10) have a higher probability of adopting advanced technologies and monitoring tools. This pattern suggests that education and professional networks can enhance awareness and access to innovative agricultural practices.
- Awareness and Expertise: Awareness and expertise levels are critical. Farmers with high awareness of specific technologies (e.g., SDI, RDI, sensors) and high expertise (Cases 1, 3, 4, 10) are more likely to adopt these technologies, indicating that knowledge and skill are significant determinants of technological adaptation.

3.3.10. Environmental Factors

- Soil Texture and Salinity: Environmental conditions significantly influence the adaptation of certain practices. For instance, farmers with clay soil (Cases 7, 8) are more likely to adopt SM as a water-saving strategy, possibly due to the higher water retention capacity of clay soils requiring more precise moisture management. Similarly, in areas with moderate salinity levels (Cases 9, 10), there is a higher probability of adopting RDI, suggesting that farmers are adapting their irrigation practices to mitigate the effects of salinity.
- Irrigation Source: The source of irrigation water (surface water vs. groundwater) might also influence the adaptation of certain technologies. For example, farmers using groundwater (Cases 4, 7, 8, 9), which is often more expensive and of variable quality, might be more inclined to adopt water-saving technologies and monitoring tools to optimize their use of this resource.

The actual selection of irrigation technologies showed a preference for subsurface drip irrigation (SDI) at 60% of small farmers who will adopt it under evaluated conditions (Table 4), compared to 40% for variable number of drippers (VND), whereas the predicted percentages were 54.4% for SDI and 39% for VND.

For water-saving strategies, the actual selections were significantly different from the predictions. Soil mulching (SM) was the preferred choice at 80%, followed by regulated deficit irrigation (RDI) at 20%, whereas the predicted probabilities were 50.9% for SM and 49.1% for RDI.

In terms of monitoring tools, the predicted percentages were 5% for metrological station (MST), 94.1% for sensors, and 0.4% for thermal imaging. However, the actual usage revealed that 30% of farmers utilized sensors, while the remaining 70% relied on observing the physical status of plants and soil, which was not accounted for in the predictions.

4. Discussion

The results of this study provide valuable insights into the factors influencing the adaptation of irrigation technologies, water-saving strategies, and monitoring tools among small farmers, particularly in the context of Egypt. The findings highlight the complex interplay between economic, educational, social, and environmental factors in determining the selection and adaptation of these practices.

4.1. Economic Factors

The study found that water cost and availability significantly impact the adaptation of irrigation technologies and water-saving strategies. As water costs increase, there is a corresponding increase in the adaptation of more efficient irrigation technologies such as variable number of drippers (VND) and subsurface drip irrigation (SDI), as well as water-saving strategies like soil mulching. Similarly, when water availability decreases, the adaptation rates for these technologies and strategies increase, suggesting that scarcity can act as a catalyst for change. This indicates that economic incentives and the reality of water scarcity are powerful drivers for the adaptation of water-efficient practices.

4.2. Educational and Social Factors

Educational level and professional organization membership were also found to influence the adaptation of irrigation technologies and water-saving practices. Higher educational levels were associated with increased adaptation rates, suggesting that knowledge and awareness play a crucial role in the uptake of these practices. Additionally, farmers who were members of professional organizations were more likely to adopt efficient irrigation technologies and water-saving strategies, indicating the importance of social networks and information sharing in promoting sustainable agricultural practices.

4.3. Environmental Factors

The study also revealed that environmental factors, such as soil texture and salinity level, play a critical role in determining the most suitable irrigation technologies and water-saving strategies. For instance, the type of irrigation technology recommended varied depending on the soil texture, with VND and SDI being preferred for light and medium soils and VND being recommended for clay soils. Similarly, the level of water salinity influenced the selection of irrigation technologies and water-saving strategies, with more efficient technologies being preferred in areas with higher salinity levels.

4.4. Implications for Policy and Practice

The findings of this study have important implications for policy makers and practitioners involved in promoting sustainable agriculture. They suggest that interventions aimed at increasing the adaptation of water-efficient irrigation technologies and water-saving strategies should consider the economic, educational, social, and environmental contexts of small farmers. For example, policies that increase the cost of water or address water scarcity could encourage the adaptation of more efficient irrigation practices. Similarly, educational programs and the promotion of professional organization membership could enhance farmers' knowledge and awareness of water-saving practices. Finally, considering the specific environmental conditions of different farming areas is crucial for the successful implementation of irrigation technologies and water-saving strategies.

In conclusion, the adaptation of irrigation technologies and water-saving strategies by small farmers is influenced by a range of factors, including economic incentives, educational levels, social networks, and environmental conditions. By understanding these factors, policy makers and practitioners can develop more effective strategies for promoting sustainable agricultural practices and ensuring the long-term viability of small-scale farming.

4.5. Discussion on Implementation, Verification, and Validation

The implementation of the expert system for recommending irrigation technologies, water-saving strategies, and monitoring tools to small farmers in Egypt has been a multifaceted process. The system's development was followed by rigorous testing to ensure its effectiveness and reliability. The verification and validation process involved running the program one hundred times for ten different small farmer conditions, comparing predicted values with actual outcomes. This section discusses the findings, focusing on the agreement rates, the impact of various factors on adaptation rates, and the implications for future research and practice.

4.6. Agreement Rates and Predictive Accuracy

The results indicate an overall agreement rate of 75% for selecting irrigation techniques, 80% for water-saving strategies, and 30% for monitoring tools. The lower agreement rate for monitoring tools can be attributed to the reliance of 70% of farmers on observation methods, which were not included in the program. This highlights the importance of incorporating traditional practices into expert systems to enhance their predictive accuracy and relevance to local contexts.

4.7. Influence of Economic, Educational, Environmental, and Social Factors

The analysis reveals that economic, educational, environmental, and social factors significantly influence the adaptation rates of different irrigation technologies, water-saving strategies, and monitoring tools. For instance, high water costs and shortages increase the adaptation of water-saving irrigation technologies like SDI and ULDI. Similarly, farmers with higher education levels and those affiliated with professional organizations are more likely to adopt advanced technologies and monitoring tools, indicating the role of knowledge and networks in technology adaptation.

Environmental conditions, such as soil texture and salinity levels, also play a crucial role. Clay soil, for example, is associated with a higher adaptation of soil mulching due to its water retention properties. Areas with moderate salinity levels see a higher adaptation of regulated deficit irrigation (RDI), suggesting that farmers adapt their practices to mitigate environmental challenges.

4.8. Implications for Future Research and Practice

The findings have several implications for future research and practice. First, the results underscore the need for expert systems to consider a broader range of factors, including traditional practices and local environmental conditions, to enhance their applicability and effectiveness. This suggests that future research should focus on integrating more comprehensive data sets that capture the full spectrum of farming practices and conditions.

Second, the study highlights the importance of education and professional networks in promoting the adaptation of new technologies. This indicates that interventions aimed at improving agricultural practices should include educational components and facilitate the formation of professional networks among farmers.

For irrigation technologies, the predictive model underestimated the preference for SDI by 5.6 percentage points and overestimated the preference for VND by 9 percentage points. This could indicate that farmers prioritize the efficiency and effectiveness of SDI over VND, possibly due to its better water distribution or ease of use, which may not have been adequately weighted in the predictive model.

The water-saving strategies show a more significant divergence, with the actual selection of SM being 29.1 percentage points higher than predicted and RDI being 29.1 points lower. This suggests that farmers may have a strong preference for maintaining SM, possibly due to its perceived benefits for crop health or yield, which were not sufficiently reflected in the predictive model.

In the case of monitoring tools, the predictive model significantly underestimated the use of physical observation of plants and soil as a monitoring method. While sensors were predicted to have a high adaptation rate of 94.1%, the actual data show that only 30% of farmers use them, with the remaining 70% relying on traditional methods. This discrepancy may be due to the cost, availability, or familiarity with new technologies, which were not considered in the model.

Finally, the results emphasize the need for tailored solutions that address the specific challenges and conditions faced by small farmers. This calls for a more localized approach to agricultural development and water management, taking into account the diverse economic, educational, environmental, and social contexts of different farming communities.

5. Conclusions

The comprehensive study on the adaptation of irrigation technologies, water-saving strategies, and monitoring tools among small farmers in Egypt has provided valuable insights into the multifaceted influences on agricultural practices. Economic factors, such as water cost and availability, were found to significantly impact the choice of irrigation methods and water conservation techniques, with scarcity and cost pressures motivating the adaptation of more efficient practices. Educational attainment and involvement in professional organizations also emerged as key drivers, indicating that knowledge and networks play crucial roles in the uptake of new technologies and strategies. Furthermore, environmental conditions, including soil texture and salinity levels, were shown to directly influence the selection of suitable agricultural practices, emphasizing the need for localized approaches. The implementation of an expert system to guide farmers in these decisions proved to be a reliable tool, demonstrating high agreement rates in its predictions, particularly for irrigation techniques and water-saving strategies. However, the lower prediction accuracy for monitoring tools suggests a need to incorporate traditional observation methods more effectively. Overall, the study highlights the potential of integrated approaches that combine technological innovation with educational and community engagement to promote sustainable agricultural development and water management in Egypt. The evaluation of the expert system showed that there were no significant differences between the predicted and actual values of irrigation technology and water-saving strategies. However, significant differences were observed among the monitoring tools because most Egyptian farmers who participated in this evaluation refused to use any of the tested monitoring tools and preferred to rely on the apparent status of the plants and soil.

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