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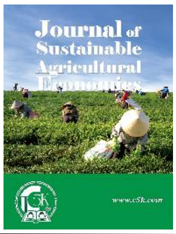

Research Article

The Economics of Water-Efficient Agriculture: Tackling Scarcity with Innovation

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ABSTRACT

Lack of water is a major challenge to irrigated agriculture, food security and rural livelihoods across the globe. This paper assesses the economic costs of implementing water-efficient technologies in the agricultural sector, such as drip irrigation, rainwater harvesting and soil moisture management. Based on case studies and pilot projects in the water-deficit areas, this work defines the cost reduction potential, the main limitations and possible directions for the development of these technologies. The study also shows that water usage decreased by half and crop yields increased by 20-30 %; thus, the program achieves both economic and resource savings. However, there are barriers, such as high capital investment costs and low knowledge among farmers about how to adopt it completely. To this end, this research outlines policy actions, funding strategies, and capacity development measures that would help create the necessary framework to enhance the uptake of water-saving irrigation and sustainable agriculture as well as optimally manage water resources for better crop production.

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1. Introduction

1.1. Background and Importance of the Research

Water is the main component of irrigation for crop and animal production, as well as food production in general. However, most of the world is experiencing water scarcity, and it is becoming worse, currently affecting 40% of the global population (United Nations, n.d.). The agricultural sector, which uses almost 70% of the total global water, has been cited as the major producer of water stress, particularly in arid and semi-arid areas (Ingrao et al., 2023). The need for food is increasing as the world population is projected to reach 9 billion by 2050, and the pressure on existing freshwater resources increases (Tripathi et al., 2019). Climate change has also made the problem worse through the deepening of drought, irregular rainfall and diminishing water resources in areas important for crop production. That is why water saving in agriculture is imperative and the basis of development and food security on the planet.

Drip irrigation, rainwater harvesting and the use of soil moisture sensors are some of the revolutionary technologies that can help solve the problem of water wastage in farming (Zhang et al., 2021). Drip irrigation systems supply water only at the root area, and the water is not easily evaporated, while rainwater harvesting systems collect rainwater to be used during dry seasons. IoT compatible soil moisture sensors help to water crops at the right time without over-wetting the soil, which is a leading cause of root rot (Bhavsar et al., 2023). However, the use of these technologies is still low given that the smallholder farmers are constrained by economic and information problems, especially in developing countries (Fadeyi et al., 2022). This research paper focuses on the economic effects of implementing water-conserving technologies in agriculture. In this context, the study's primary focus has been on the cost-saving benefits, challenges and applicability of the techniques in areas constrained by water availability, offering practical recommendations to policymakers, farmers and other stakeholders.

1.2. Current Challenges in Water Management in Agriculture

Another way traditional methods of irrigation have caused a tremendous waste of water, especially in the arid areas of the agricultural sector. Some of the most pressing challenges include:

1.2.1. Inefficient Irrigation Practices

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In many farming systems, more traditional methods, including flood and furrow irrigation, are still prevalent. Such methods are extremely costly and wasteful and can result in water losses of between 30% and 60% through evaporation, seepage and runoff (Samir et al., 2023). For example, flood irrigation, which is widely used in South Asia, causes overwatering and nutrient leaching, and soil fertility depletes after some time.

1.2.2. Financial Barriers

The high costs of irrigation technologies like drip irrigation and soil moisture sensors, uptake is very low due to costs particularly among small and marginal farmers (Marimuthu et al., 2024)). A usual drip irrigation system installation may range from $800 to $2,500 per acre; therefore, it is unaffordable for most farmers who cannot attract outside funding.

1.2.3. Knowledge and Awareness Gaps

Most farmers are ignorant of water-efficient technologies or their future implications. Again, they do not have access to training programs and technical support to acquire and use these systems efficiently.

1.2.4. Institutional and Policy Gaps

Lack of sound policies, inadequate subsidies, and segmented extension services hinder the adoption and use of water-conserving technologies. For example, even though several governments offer subsidies to farmers who use drip irrigation, the many hoops that must be jumped through and long waiting periods dissuade farmers from applying.

1.3. Role of Innovation in Addressing Water Scarcity

Advancements in technology provide the solution to the problems and inadequacies of conventional water management strategies in agriculture. Water-efficient technologies offer multiple advantages:

1.3.1. Reducing Water Consumption

Automated drip irrigation systems have been found to be as effective as the traditional methods, with the use of half the amount of water. Rainwater management can also support the irrigation requirement in addition to the harvest during wet seasons.

1.3.2. Enhancing Productivity

This is because the water delivery is made efficient to facilitate meeting the crops' water requirements, thus improving growth and yield. Research shows that by using drip irrigation, crop productivity can be boosted by 25-30%, which makes the solution economically profitable for farmers.

1.3.3. Lowering Costs

While capital costs are relatively high, the payback period is short because of the savings in water and energy required by these technologies. For example, soil moisture sensors help farmers in irrigation, which in turn allows them to avoid water wastage and the costs implied in pumping.

1.3.4. Building Climate Resilience

Water-efficient technologies enable farmers to adapt to climate changes, such as droughts and irregular rainfall, which are becoming more common. Drip irrigation, accompanied by soil moisture information, helps to use a limited amount of water at the right time at the right stage of crop development.

1.3.5. Environmental Benefits

These technologies ensure that the use of water is reduced and thus the development of salinization and waterlogging, which are unfavorable to the health of the soil. Also, pumping water has lower energy consumption in relation to greenhouse gas emissions, which aims at sustainable agriculture.

1.4. Significance of the Study

Water-saving technologies have already been demonstrated to have positive effects. However, knowledge of their effects on the economy, especially in water-security countries, still needs to be gained. This study is, therefore, relevant in filling this gap by estimating the cost savings, yield improvements and overall economic rationality of implementing these technologies. Further, it outlines reasons why adoption has yet to be achieved, such as financial constraints and lack of adequate knowledge and provides a course of action to achieve the goals. Therefore, this research's implications extend to policymakers, stakeholders in the agricultural sector and international development agencies. This paper shows that water-efficient agriculture is not a pipe dream and outlines how to replicate these innovations and best practices in sustainable water management.

2. Materials and Methods

2.1. Study Scope and Objectives

This study aimed to assess the economic costs of implementing water conservation measures in irrigated agriculture in the USA, with special reference to California, Arizona and Texas. It also aimed to assess the benefits and challenges of using such technologies as drip irrigation, rainwater harvesting and soil moisture sensors in terms of input cost, output gains and barriers. Qualitative and quantitative data collected from pilot programs, farmer interviews and policy reviews were combined.

2.2. Data Collection

2.2.1. Primary Data

Primary data were obtained via survey questionnaires administered to thirty farmers operating in areas experiencing dry conditions, the Central Valley of California and the Colorado River Basin in particular. These interviews aimed at understanding farmers' perceptions of the economic benefits based on water-efficient technologies, as well as the operational complexities and sustainability of the technologies implemented. Furthermore, surveys of pilot programs using these technologies were conducted over two consecutive growing seasons to determine water conservation, energy usage, and crop yield.

2.2.2. Secondary Data

Secondary data were collected from government reports, case studies, and market analysis studies. Data on water conservation programs and adoption were obtained from the USDA's Natural Resources Conservation Service (NRCS). Literature sources like the Sustainable Groundwater Management Act (SGMA) of California were used to get insights regarding institutional structures and incentives. To this, cost and operational data of the technologies under study were complemented by information from market reports such as the Irrigation Association. The research focused on three primary technologies, chosen for their potential to improve water use efficiency and deliver economic benefits:

2.3. Technologies Studied

The research focused on three primary technologies, chosen for their potential to improve water use efficiency and deliver economic benefits:

2.3.1. Drip Irrigation Systems

Drip irrigation was assessed to determine the efficiency of the delivery of water to the root zone of plants with minimal losses through evaporation and runoff. The study focused on its application mainly in high-value crops such as almonds and vineyards grown in California's Central Valley.

2.3.2. Rainwater Harvesting Systems

An assessment of rainwater harvesting as a measure of providing irrigation support in other small farms in Texas was conducted. These systems comprise water bars on rooftops and tins where the water is stored in readiness for when the farmers need to water the crops, especially during dry seasons.

2.3.3. Soil Moisture Sensors

A component that was investigated for its role in precision irrigation was the soil moisture sensor usually applied in Arizona's row crop farms. These sensors suddenly gave real-time soil moisture information that was important when it came to water application.

2.4. Analytical Framework

2.4.1. Economic Analysis

Cost and revenue analysis comprises cost/revenue benefit analysis, cost/revenue payback period analysis, and yield gain analysis. In particular, the study made an overarching analogy of the initial costs of installation and operation of each technology and subsequent economic advantages in terms of water and energy consumption. For instance, drip irrigation systems were examined based on their efficiency in using half of the normal amount of water and increasing crop production by 25 – 30%.

2.4.2. Environmental Impact Assessment

According to the environmental assessment, the aim was to minimize the use of water and energy while improving the health of the soil. Soil moisture sensors controlled drip irrigation systems in California's Central Valley learned that runoff and evaporation are minimized and that water is well correlated with crop germination.

2.4.3. Adoption Barriers Analysis

This study also examined the challenges to adoption through interviews with farmers and analysis of policies. Based on the nature of the barriers identified, they included barriers to financial potential, including high initial costs of technologies, poor information on available subsidies, and barriers to infrastructural potential, including poor access to installation services.

2.5. Data Analysis

Quantitative and qualitative data analysis techniques were employed to provide a comprehensive understanding of the impacts of water-efficient technologies:

2.5.1. Quantitative Methods

This paper used statistical tools to create regression models regarding the adoption of technologies and economic status. Descriptive statistics provide means of some variables, such as water usage, cost, and yield, while figures of adoption, bar charts, and line graphs provide comparative costs

2.5.2. Qualitative Methods

Qualitative data was also analyzed to perform a thematic analysis of farmers' interview responses and establish motivational and demotivational factors repeatedly mentioned by the respondents. These qualitative data were helpful in situating quantitative data to provide a comprehensive perception of the adoption process.

2.6. Study Sites

The research focused on three key regions in the United States, each chosen for its unique agricultural and climatic characteristics:

1. **California's Central Valley**

This area produces high-value crops, so it was chosen as a sample location for drip irrigation systems. The pilot programs showed the conservation and increase of yields under extreme water limitations resulting from the SGMA mandates.

2. Colorado River Basin (Arizona)

This site targeted data concerning the application of the soil moisture sensor in row crop growing, more so in corn and cotton crops. Hypsometers and other sensors helped farmers accurately control irrigation, saving water and energy at the same time.

3. Texas Plains

Rainwater harvesting systems were studied in small farms within this region, where they proved effective in reducing irrigation costs during extended dry periods.

2.7. Study Limitations

There were limitations in this study, and they included the following: First, due to the observation period of only two seasons, the effects of these technologies in several years, both on the economy and environment of the regions, will continue to remain not completely understood. Further, the study bears constraints in that the samples were drawn within the Midwestern United States only and, therefore, cannot be used to make a generalization of other parts of the United States. Last, the decision to select farmers for interviews, which included some of those already used to water-saving technologies, may have skewed this assessment of adoption challenges.

3. Results and Discussion

3.1. Water and Cost Savings of Water-Efficient Technologies

Case studies on water-saving technologies in agriculture (Fig. 1 & fig. 2) showed that the new technologies led to remarkable water and operational cost savings and increased crop yield. For example, the use of drip irrigation permanently minimized water withdrawal by 50 percent compared to the use of flood irrigation. This was obtained by providing the plant with water in the root area hence reducing the amount of water evaporated as well as that which forms a part of runoff. Also surveyed farmers measured yield enhancement in a range of 25–30%, especially, almonds, grapes, and tomatoes produced in the central valley of California.

Rainwater harvesting systems also yielded an optimum result, ranging from 30-40 percent of seasonal rainfall captures. In Texas, farmers used these systems to augment irrigation in the dry, thereby minimizing the use of pumpage of groundwater. Besides saving water, it reduces the amount spent on irrigation, ranging from $50-$100 per acre per year. Precision irrigation was also improved by the use of soil moisture sensors in vegetation management. These sensors in Arizona provided the row crop farmers with the ability to cut the wastage of water by 35 percent and energy by 20 percent because over-irrigation was averted, shown in Table 1.

Table 1. Water and Cost Savings Across Technologies

Technology	Water Savings (%)	Cost Savings (USD/acre)	Yield Increase (%)
Drip Irrigation	50	$150–$300	25–30
Rainwater Harvesting	40	$50–$100	N/A
Soil Moisture Sensors	35	$75–$150	20

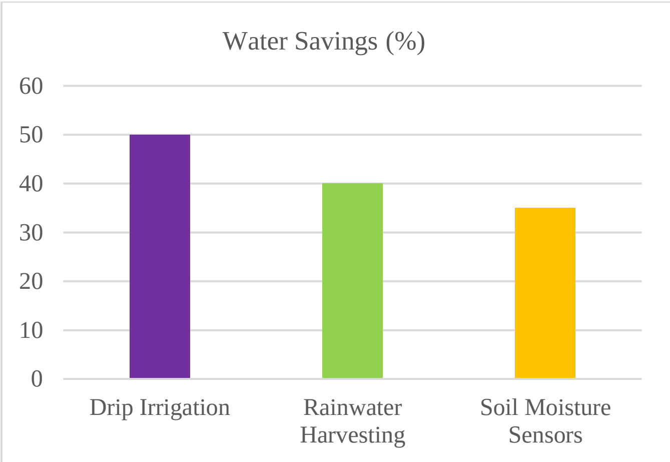

Fig.1. Water Savings

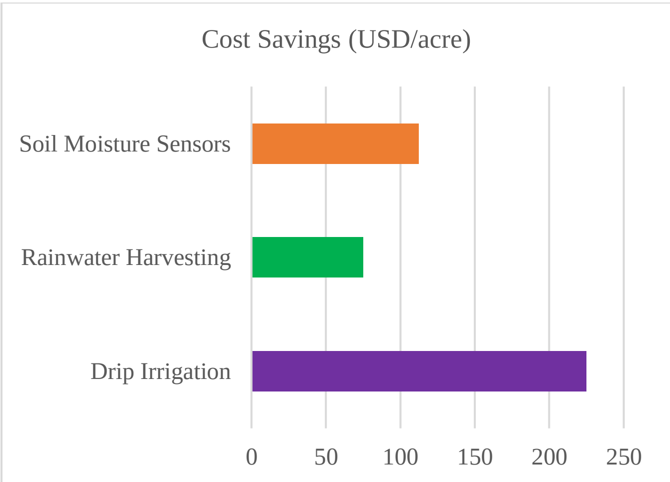

Fig.2. Cost Savings

3.2 .Adoption Barriers

Although there are positive findings associated with the use of water-efficient technologies, they have yet to be widely implemented because several barriers exist. The main problem area that was identified was the high levels of initial cost. A drip irrigation system requires an initial investment of $800 -$2500 per acre, depending on the crops to be irrigated and the regions of installation. Since these expenses are usually high, many small-scale farmers are being affected despite themselves being a large chunk of employees in the farming industry in areas like California and Texas. The third important obstacle relates to ignorance about the issue and the need for specialist skills. Farmers interviewed stated that they knew nothing out of government support that could help offset costs as envisaged in those technologies or training programs that could assist them in overcoming some of the challenges towards the adoption of such technologies. For instance, while USDA programs may be available to help pay for drip irrigation systems, farmers never apply for such schemes due to long permits and complicated paperwork, as presented in Fig. 3.

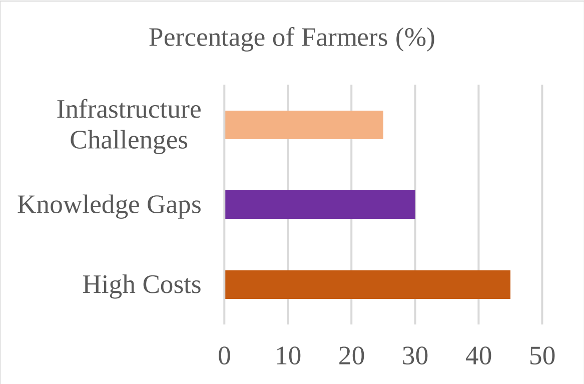

Fig.3. Percentage of Farmers

3.3. Economic Benefits and Payback Periods

The economic analysis showed that while high upfront cost is attached to water-efficient technologies, they are economically feasible in the long run. The payback period for the drip irrigation system was found to be the shortest, averaging between 3 and 7 years. These periods depended on factors such as the type of crop, the cost of water, and local subsidies. For instance, growers of almonds in California benefited from shorter payback periods because the crops fetched good prices and saved much water through efficient watering.

Although the IoT-integrated devices cost slightly more because of the functionality of the device, the long-term cost-savings of the soil moisture sensors were evident in terms of irrigation and the associated energy costs of over-irrigation. Rainwater harvesting systems took the longest time to recover their costs, given that their performance depended on rainfall regimes and storage facilities in the region. That said, these systems offered important augmenting irrigation, especially during times when water was scarce in areas with seasonal droughts, thus making crops viable.

3.4. Environmental Impacts of Adoption

In addition to these economic returns, the implementation of water-efficient technologies was also found to offer significant environmental benefits (Fig. 4). When drip irrigation systems were used in California's Central Valley, water runoff and soil erosion were cut by 60%. This improvement was particularly important in helping to prevent nutrient leaching, which can reduce the nutrient content of soil and contaminate water sources. Soil moisture sensors in Arizona enabled precise control of water usage, avoiding the development of secondary effects such as salinization and waterlogging, which are typical of irrigation systems. Through the regulation of the right amount of water in the soil, these sensors help conserve the soil and improve plant growth. Like rainwater harvesting systems, water wells in Texas were also decreased to minimize the stress on aquifers and thus promote the sustainability of water in Texas in the long run.

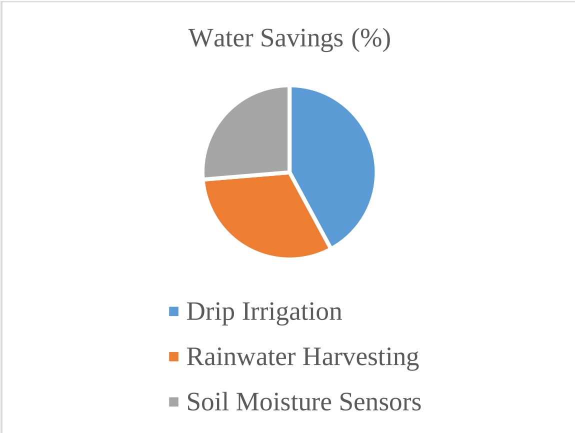

Fig.4.Water Savings

3.5. Implications for Policy and Practice

The results point to the need for policy solutions that would help increase the uptake of water-saving technologies. The major challenge is that the initial costs of installation are very high, and thus, subsidies and financial incentives should be enhanced. For example, increasing the reach of the USDA programs to offer direct funds instead of matching fund programs may enhance uptake by small-scale farmers.

The same applies to capacity-building initiatives as well. At this time, farmers may need to fully comprehend the operational or economic advantage of these technologies, which suggests that creating regional training centers and demonstration plots may be appropriate. Cooperation with private sector companies could also improve installation and maintenance services affordability and tackle infrastructural issues. Water-saving technologies need to be incorporated into the general climate change adaptation frameworks. Since droughts and fluctuating weather conditions are on the rise, these innovations offer a sustainable way of increasing the yield of crops in agriculture without depleting water sources.

4. Conclusion

Technological advancement in irrigation technology is a way forward to the twin problems of water conservation and food security. With water conservation ranging from 30–50% and yield enhancement of 25–30%, technologies like drip, rainwater harvesting, and moisture sensors should be adopted. However, the use of modern planting materials is limited by some factors, such as high initial costs and lack of information, which leaves many users, such as smallholder farmers, behind. Policymakers should focus on incentives, capacity enhancement, and partnerships to encourage the use of effective water technologies. For training, demonstration, and financial incentives, large-scale implementation requires farmer participation, and this can be achieved through more investment in the programs.

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