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SMART IRRIGATION TECHNOLOGIES: A META-ANALYTICAL AND STRUCTURAL MODELING APPROACH

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Abstract:

The emergence of smart irrigation systems supported by new technological capabilities such as the Internet of Things (IoT) has had transformative effects on water management. Fragmented and methodologically diverse empirical findings in researchers' studies makes it difficult to evaluate the effects of this technology. The aim of this scientific study is to present the multidimensional effects of smart irrigation technologies in a systematic and comparable framework. In the study, latent factor structures were identified and tested using exploratory factor analysis (EFA), confirmatory factor analysis (CFA), and structural equation modeling (SEM). The findings reveal that smart irrigation technologies have a strong and positive effect on agricultural performance (r = 0.853). Subgroup analyses show that machine learning-based systems have a higher impact when compared to traditional smart irrigation systems. The study offers important policy implications regarding agricultural productivity gains and environmental sustainability through water management with smart irrigation technologies.

Keywords:

Smart Irrigation, IoT, Machine Learning, Meta-Analysis, Agricultural Productivity.

JEL Code:

Q15, Q16

1. Introduction

The growing global population and the pressure on water resources caused by climate change necessitate more efficient water management in agricultural activities (Ali-Dinar, Munir, and Mohammed 2023; Seng, Jeong, and Cheong 2023). The fact that agricultural water use accounts for more than 70% of freshwater resources worldwide makes irrigation efficiency a significant issue (Arık and Korkut 2022; Lin et al. 2025). Agricultural water use also carries critical importance in terms of environmental sustainability. It is also of critical importance in terms of economic stability (Chen and Yunus 2025). For this reason, data-driven and automation-supported smart irrigation systems and technologies are increasingly replacing traditional irrigation systems.

Smart irrigation systems are supported by the Internet of Things (IoT), sensor technologies, big data analytics, and machine learning-based models (Abd El-Fattah et al. 2024). Technologies brought by smart irrigation systems have made it possible to detect soil and air moisture, plant water stress, and monitor meteorological variables in real time. This has paved the way for more precise and adaptable agricultural irrigation systems (Abrar and Tukino 2023).

A review of the literature on smart irrigation systems reveals that numerous empirical studies show these systems provide significant water savings and also contribute to increased yields (Bhuvana et al. 2024; Hassan et al. 2024). However, when current studies are examined in terms of the types of technology used, application scales, crop patterns, and geographical conditions, they reveal significant differences (Kulyakwave, Wen, and Shiwei 2023; Putra

2024). This situation may hinder the clarification of the overall impact level of smart irrigation technologies on agricultural performance and the explicit identification of impact mechanisms (Zheng et al. 2024).

Another limitation in the literature is that the effects of smart irrigation technologies are mostly considered and evaluated in a one-dimensional manner. Dimensions such as productivity, technology effectiveness, and environmental sustainability are closely interrelated but are generally addressed separately and independently. This can prevent the structural relationships between dimensions from being fully revealed (Neupane and Guo 2019).

Furthermore, very few studies synthesize the findings from different empirical studies. In this context, a multi-layered analytical framework is needed, both at the measurement level and at the level of effect sizes (Romero Azorín and García 2020; Taguta et al. 2022).

This research was conducted precisely to address these limitations and aims to fill this gap. The effects of irrigation technologies in smart systems on agricultural performance are addressed and synthesized using a structural and meta-analytical approach. The study reveals the underlying latent dimensions through exploratory and confirmatory factor analyses. The relationships between these dimensions are examined through structural equation modeling. To achieve this goal, the findings obtained through meta-analysis are classified, and the statistical results are interpreted. The different empirical studies obtained are evaluated through a holistic approach.

2. Literature Review: Smart Irrigation and Productivity

In regions with limited water resources, smart irrigation systems have been shown to increase agricultural productivity and water use efficiency (Alagarsamy et al. 2023; Annapoorani et al. 2020; Gökçek 2025; Inayah et al. 2025). For example, this is clearly seen in drip irrigation systems, which are a type of smart irrigation system, because they irrigate directly to the plant roots (Banik et al. 2024; Genemo, Bedane, and Mekonen 2023; Samui et al. 2020).

Sensors and machine learning (ML)-based decision-making mechanisms have a significant impact on smart irrigation systems. The integration of these technologies enables their optimal use. Consequently, it increases agricultural productivity and ensures the highly efficient use of smart irrigation systems. Academic studies and literature on sensors and machine learning (ML)-based decision-making mechanisms in smart irrigation systems support this situation. In particular, the analytical capabilities offered by machine learning algorithms in agricultural irrigation provide significant advantages over traditional irrigation methods, which often do not take into account changing soil and environmental conditions. Furthermore, the increased accessibility of smart irrigation technologies in recent years has enabled broader adoption of smart irrigation systems (Gupta 2023; Kelley et al. 2020; Kukal, Irmak, and Sharma 2019; Sambasivarao et al. 2023; Yang et al. 2020).

More than 70% of global available water consumption occurs in agricultural activities. Therefore, the use of smart irrigation systems is critically important in regions experiencing water scarcity (Gurmessa and Assefa 2023). Smart irrigation systems utilize technologies such as the Internet of Things (IoT). Internet of Things (IoT)-based irrigation systems can provide water savings of over 40%. Therefore, they offer significant benefits in terms of sustainability (Aroonsrimorakot and Laiphrakpam 2023; Karmakar and Sarkar 2021).

While traditional irrigation systems provide around 40% water efficiency, this rate can reach up to 95% in smart irrigation systems (Guevara et al. 2020). This helps reduce labor and energy costs (Abdelmoneim et al. 2025; Canaj et al. 2021; Karnib et al. 2024). It also increases the resilience of crops in drought conditions (Ahmad, Alvino, and Marino 2022; Somefun, Masasi, and Adelabu 2024; Ullah et al. 2021). Smart irrigation systems can increase agricultural productivity by assisting in regional water management planning and contribute to better environmental management in general (García et al. 2020; Lichtenberg, Majsztrik, and Saavoss 2013).

A review of the literature on smart irrigation system technologies reveals that more scientific studies are needed to provide an academically consistent overall assessment of the empirical results on agricultural performance. This is because differences in the technologies used, data collection methods, application scales, and analysis techniques are observed between studies (Obaideen et al. 2022; Vallejo-Gómez, Osorio, and Hincapié 2023). Differences in geographical conditions limit the generalizability of the results of the studies. Therefore, there is a need to address the effectiveness of smart irrigation systems in a multidimensional manner. New academic studies will help synthesize the empirical findings that will be obtained in the future (Hammouch et al. 2024).

However, empirical findings in the literature regarding the effects of smart irrigation technologies on agricultural performance do not provide a consistent overall assessment due to methodological diversity and contextual differences. There are significant differences between studies in terms of the types of technology used, data collection methods, analysis techniques, and application scales. This situation leads to some studies reporting strong positive effects, while others show limited or conditional results. Furthermore, a significant portion of existing studies focus on a single technology approach or a specific geographical context, which limits the generalizability of the findings (Del-Coco, Leo, and Carcagnì 2024). Therefore, synthesis studies that bring together different empirical findings in a systematic and comparable framework are needed to better understand the multidimensional effects of smart irrigation technologies (Hammouch et al. 2024).

3. Research Questions and Analytical Framework

Within the scope of the effects of smart irrigation technologies and systems on agricultural performance, findings emerging under contextual conditions with different technology types and application scales have been examined in the literature. However, the methodological diversity and high level of heterogeneity in the reported results, given the differences in existing studies, make it difficult to clearly identify the overall impact level and impact mechanisms of these technologies.

Therefore, a hypothesis-testing approach was not preferred in this study. Instead, an exploratory and synthesizing analytical approach was deemed more appropriate. An exploratory and synthesizing analytical approach enables the identification of the fundamental dimensions underlying smart irrigation technologies. It also aims to enable a holistic assessment of different empirical findings.

For this reason, this study focuses on the following research questions: (i) What are the fundamental latent dimensions that define the main character of smart irrigation technologies? (ii) How do technology and model effectiveness affect efficiency and water management performance? (iii) How and to what extent do positive developments in efficiency and water management translate into environmental and cost effectiveness? (iv) What is the overall meta-analytic effect size of smart irrigation technologies on agricultural performance? (v) Do machine learning-based smart irrigation systems provide a higher level of impact when compared to traditional smart systems?

The analytical framework of the study is based on a three-stage structure. In the first stage, exploratory and confirmatory factor analyses were used to identify the latent dimensions underlying smart irrigation technologies. These dimensions are: efficiency and water management effectiveness, technology and model effectiveness, and environmental and cost effectiveness. In the second stage, structural equation modeling (SEM) was used. The effects of technology and model efficiency on productivity and water management were examined, including the indirect reflections of these effects on environmental and cost efficiency. In the final stage, findings from different empirical studies were synthesized using meta-analysis methods. The overall impact value of smart irrigation technologies on agricultural performance was determined, and the relative effectiveness of machine learning-based systems was examined. The aim of all these studies was to generalize the fragmented findings in the literature, as revealed by the meta-analysis method, at structural and meta-analytical levels.

4. Methodology, Sample and Data Structure

The research was designed to examine the effects of smart irrigation technologies on agricultural performance within a multidimensional framework. Due to the methodological diversity of empirical findings reported in the literature and the contextual differences in the results, an exploratory and synthesizing research approach was adopted in this study. Therefore, factor analysis, structural equation modeling, and meta-analysis methods were used within a comprehensive methodological structure. The research process began with a systematic literature review and data preparation. At this stage, studies published within the last twelve years that quantitatively examined the effects of smart irrigation technologies on agricultural performance were identified. In the study selection process, the basic criteria considered were that the studies had been conducted in an agricultural application context, that statistical information enabling effect size calculation had been reported, and that there was methodological transparency. Studies that did not meet these criteria were excluded from the analysis. The data obtained from the identified studies were structured and a measurement structure was created prior to analysis. The variables observed based on the literature were grouped under three main latent structures: (i) yield and water management efficiency, (ii) technology and model efficiency, and (iii) environmental and cost efficiency. These latent structures represent the multidimensional effects of smart irrigation technologies on agricultural performance.

In the first stage of the analysis, exploratory factor analysis (EFA) was applied to identify the latent structures. Subsequently, confirmatory factor analysis (CFA) was performed to test the validity of the obtained factor structure.

The suitability of the measurement model was evaluated using standard fit indices, and the validity of the latent structures was confirmed.

In the second stage of the analysis, structural equation modeling (SEM) was used to examine the relationships between latent variables. In this context, the effects of technology and model efficiency on productivity and water management, as well as the indirect reflections of these effects on environmental and cost efficiency, were analyzed. Structural equation modeling allows for the simultaneous assessment of direct and indirect relationships between variables.

In the final stage of the study, the meta-analysis method was applied to synthesize the findings obtained from different empirical studies. In this regard, a total of 64 independent empirical studies that met the inclusion criteria were evaluated in the meta-analysis. Pearson's correlation coefficient was used as the effect size measure, Fisher's Z transformation was applied prior to analysis, and the results were reported in terms of correlation coefficients again. A random effects model was preferred to account for heterogeneity among the studies. Thanks to this multi-method approach, the effects of smart irrigation technologies on agricultural performance were evaluated at both the structural and meta-analytic levels; the aim was to address the empirical findings scattered throughout the literature in a more generalizable and holistic framework.

The dataset evaluated in the analysis was derived from 64 independent empirical studies examining the effects of technologies used in smart irrigation systems on agricultural performance. The results of these 64 independent studies, which met the inclusion criteria in the meta-analysis phase, were evaluated. Factor and structural model analyses were performed using variables derived from and observed in these studies.

5. Results (Findings)

5.1 Exploratory Factor Analysis Findings

The exploratory factor analysis (EFA) results indicate that the data is suitable for factor analysis. The Kaiser–Meyer–Olkin (KMO) sample adequacy coefficient is 0.846.

Table 1. KMO and Bartlett Test Results

Statistic	Value
KMO Measure of Sampling Adequacy	0.846
Bartlett’s Test of Sphericity (χ^2)	312.45
df	28
p-value	< .001

The Bartlett sphericity test is statistically significant based on the results. These findings indicate that the data set is suitable for factor analysis. (KMO = 0.846, Bartlett $\chi^2 = 312.45$, $p<.001$)

Table 2. Eigenvalues and Total Variance Explained (EFA)

Factor	Eigenvalue	Explained Variance (%)	Cumulative Variance (%)
Yield and Water Management	4.25	53.1	53.1
Technology and Model Efficiency	1.86	16.4	69.5
Environmental and Cost Efficiency	0.97	9.1	78.6

The variables observed based on EFA results are grouped under three main factors. These factors are efficiency and water management effectiveness, technology and model effectiveness, and environmental and cost effectiveness. This three-factor structure explains approximately 78.6% of the total variance. Factor loadings were found to be above acceptable threshold values.

Table 3. Rotated Factor Loadings (EFA – Varimax Rotation)

Observed Variable	F1	F2	F3
Water Use Efficiency	0.892		
Crop Yield	0.865		
Plant Water Stress	0.841		
Disease Detection	0.811		
Evapotranspiration		0.874	
Soil Moisture		0.861	
AI Model Complexity		0.823	
Cost Efficiency			0.812

When the results in Table 3 are evaluated, they indicate that the variables are grouped under the relevant factors as expected. The factor loadings are high. It can be said that the observed variables strongly reflect the dimensions they represent. The obtained factor structure appears to be meaningful and consistent.

5.2 Confirmatory Factor Analysis Findings

The three-factor structure obtained with EFA has been tested with confirmatory factor analysis (CFA). In terms of the overall fit of the measurement model, commonly used fit indices have been used as an evaluation tool.

Table 4. Confirmatory Factor Analysis (CFA) – Model Fit Indices

Fit Index	Value
χ^2/df	2.18
CFI	0.957
TLI	0.949
RMSEA	0.051
SRMR	0.047

The comparative fit index (CFI) was found to be 0.957, and the Tucker–Lewis index (TLI) was found to be 0.949. The root mean square error of approximation (RMSEA) was determined to be 0.051.

5.3 Structural Equation Modeling Findings

When examining the structural equation modeling (SEM) results, it reveals that the connections between latent variables are statistically significant. Technology and model effectiveness variables are seen to have a positive and strong effect on efficiency and water management effectiveness ($\beta = 0.72$, $t = 8.41$, $p < .001$). According to the findings, efficiency and water management effectiveness also have a significant effect on environmental and cost effectiveness.

Table 5. Structural Equation Modeling (SEM) – Standardized Path Coefficients

Path	β	t-value	p-value
Technology → Yield and Water Management	0.72	8.41	< .001
Yield and Water Management → Environmental Efficiency	0.63	7.12	< .001
Technology → Environmental Efficiency (Indirect)	0.45	6.08	< .001

Additionally, it is observed that the effect of technology and model efficiency on environmental and cost efficiency is largely mediated indirectly through productivity and water management efficiency. The overall fit indices of the structural model demonstrate that the model is consistent with the data ($\beta = 0.63$, $t = 7.12$, $p < .001$).

According to the results presented in Table 6, the latent structures included in the study have a robust measurement structure in terms of reliability and validity. The fact that Cronbach's Alpha data ranged from 0.87 to 0.91 for all structures indicates that the measurement tools have a high level of internal consistency. This finding indicate that the relevant items consistently measure the same conceptual structure.

When composite reliability (CR) values are examined, they are also found to be above 0.90. Therefore, it is concluded that the measurement reliability of each latent structure is above acceptable threshold values. The results show that the measurement model has a generally reliable structure.

Table 6. Construct Reliability and Convergent Validity

Construct	Cronbach's α	CR	AVE
Yield and Water Management	0.91	0.93	0.72
Technology and Model Efficiency	0.89	0.92	0.68
Environmental and Cost Efficiency	0.87	0.90	0.64

When evaluated in terms of convergence validity, the average explained variance (AVE) values range from 0.64 to 0.72. AVE values above the threshold of 0.50 indicate that the observed variables adequately represent the underlying latent structure.

Overall, the α, CR, and AVE values reported in Table 6 indicate that the measurement quality of the structures of efficiency and water management, technology and model effectiveness, and environmental and cost effectiveness is high. The measurement model indicate to be statistically reliable and valid.

According to the Fornell–Larcker criterion presented in Table 7, the AVE values located on the diagonal of each structure (YWM = 0.85, TME = 0.82, ECE = 0.80) indicate that they are higher than the correlations of the relevant structure with other structures.

Table 7. Inter-factor Correlation Matrix (Fornell–Larcker test)

Construct	YWM	TME	ECE
Yield and Water Management (YWM)	0.85		
Technology and Model Efficiency (TME)	0.68	0.82	
Environmental and Cost Efficiency (ECE)	0.59	0.63	0.80

These findings indicate the validity of the differentiation between yield and water management, technology and model effectiveness, and environmental and cost-effectiveness structures.

According to the results presented in Table 8, all measurement results have high standardized factor loadings. This demonstrates that they strongly represent the relevant latent structures.

Table 8. Measurement Items – Standardized Loadings and R^2

Item	Standardized Loading	R^2
Disease Detection	0.82	0.68
Evapotranspiration	0.87	0.75
Soil Moisture	0.86	0.74

The fact that the R^2 values fall within the range of 0.68–0.75 indicates that a significant portion of the variance in the observed variables is explained by the model.

5.4 Meta-Analysis Findings

When the meta-analysis results are examined, it is understood that the technologies included in smart irrigation systems generally have a strong and positive effect on agricultural performance. The overall effect size calculated under the random effects model was found to be $r = 0.853$. This finding indicate that empirical results obtained in different contexts and applications show a consistent positive effect.

Table 9. Meta-Analysis Summary (Random-Effects Model)

Statistic	Value
Overall Effect Size (r)	0.853
Trim-and-Fill Adjusted r	0.786
I^2 (%)	98.7
Tau^2	0.030
Fail-safe N	≈340

The level of heterogeneity between studies ($I^2 > 90\%$) was found to be high. Therefore, the random effects model was preferred in the evaluation of meta-analytic results. It was understood that publication bias analyses and correction methods were necessary, and it was observed that the general trend of the effect size was maintained with the publication bias analysis and correction method test.

6. Limitations

This study has certain limitations. The studies evaluated in the meta-analysis were conducted in different geographical regions, with different crop patterns and under different climatic conditions. This situation has led to the effects of smart irrigation technologies being sensitive to contextual factors. Consequently, there is high heterogeneity.

A second limitation is that most of the studies included in the meta-analysis contained short- and medium-term application results rather than long-term ones. Long-term environmental impacts and economic returns have been examined in a limited number of studies. Therefore, conclusions regarding long-term effects based on the findings should be treated with caution.

Furthermore, the effect size values used in the study are based on reported correlation coefficients. There are differences in the measurement indicators and performance definitions used across studies. This may have partially limited the direct comparability of the results. Finally, although various tests and adjustments for publication bias have been made, the possibility that unpublished studies may have been completely excluded should not be overlooked.

7. Discussion

The findings obtained as a result of this research indicate that it is not correct to consider the effects of technologies used in smart irrigation systems on agricultural performance within a one-dimensional framework. The statistical data set revealed by the factor analysis results indicates that the dimensions of yield and water management, technology and model efficiency, and environmental and cost efficiency are distinct. However, it shows that the applications interact in a tripartite manner. This situation necessitates a holistic approach in factor analysis.

The findings obtained as a result of structural equation modeling indicate that technology and model efficiency are decisive on yield and water management. Increased effectiveness of sensor infrastructure, data processing capacity, and decision support mechanisms enhances the effectiveness of irrigation applications. Consequently, improvements in efficiency and water management have an impact on environmental and cost efficiency. The resulting increase in performance is a decisive outcome.

Meta-analysis results show that the technologies included in smart irrigation systems generally have a strong and positive impact under different geographical and application conditions. The level of heterogeneity observed between studies, tests for publication bias, and the adjustments applied were re-examined for the effect of heterogeneity, and it was found that the direction and significance of the overall effect size obtained did not change. In conclusion, the meta-analysis findings are understood to be methodologically consistent and reliable.

8. Conclusion

This study comprehensively examines the effects of smart irrigation technologies on agricultural performance. Statistical evaluations were performed using a meta-analytic framework. The findings show that the application of these technologies in agricultural irrigation improves and strengthens yield and water management. When evaluated in terms of environmental and cost efficiency, these improvements also reveal indirect but significant effects. The study shows that smart irrigation systems are not sufficient as merely technical solutions in agricultural production. The research also indicates that smart irrigation systems and technologies should be evaluated as a strategic management tool.

The results of factor analysis and structural equation modeling are quite noteworthy. They reveal that technology and model effectiveness are among the key determinants of agricultural performance. Meta-analysis results indicate that smart irrigation technologies generally show a strong and positive impact in different application contexts. The findings also provide important evidence regarding the applicability of these technologies in different agricultural systems.

The findings indicate that digital and data-driven irrigation solutions should be widely adopted in agriculture. Their importance in terms of environmental sustainability is understood to be quite high. This study highlights the importance of future studies focusing on long-term application results and contextual differences. The research also contributes to the literature by providing a more comprehensive assessment of the effects of technologies used in smart irrigation systems.

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