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Innovation Driven Water Sustainability: The Role of Technological Innovation in Achieving Water Security in Saudi Arabia

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ABSTRACT

This study examines the relationship between technological innovation and water sustainability in Saudi Arabia, a nation facing extreme water scarcity. Using a mixed-methods approach, we surveyed 425 water management professionals across agricultural, industrial, municipal, residential, and technology sectors between March and August 2024, supplemented by 32 stakeholder interviews. Five hypotheses were tested regarding innovation adoption, organizational factors, technology acceptance, regulatory support, and sectoral differences.

Results confirm all five hypotheses. Water recycling systems (71.3%) and precision agriculture (68.9%) showed highest adoption rates. Innovation adoption strongly predicted sustainability outcomes ($r = .726$, $p < .001$), with leadership support emerging as the strongest predictor ($\beta = .327$). High-innovation adopters achieved 2-3 times better performance across sustainability metrics. Significant sectoral differences exist, with technology providers and industrial sectors leading adoption. High initial costs remain the primary barrier (68.2%), while regulatory support significantly moderates innovation effectiveness. Most innovations demonstrate positive ROI within 4-6 years.

Qualitative findings revealed five themes: innovation as strategic necessity, implementation gaps due to financial constraints, importance of demonstration projects, need for integrated policy approaches, and critical cultural-behavioural dimensions. These results provide evidence-based guidance for policymakers and practitioners advancing water security through technological innovation in arid regions..

Keywords: Water sustainability, technological innovation, water security, Saudi Arabia, sustainable development

INTRODUCTION:

Technological innovation is crucial for water security in Saudi Arabia through advancements in desalination, wastewater reuse, and smart water management. Innovations like more efficient desalination plants, the use of AI and automation in smart water infrastructure, and new technologies for water treatment and transportation are essential for overcoming water scarcity driven by climate and population growth. These efforts are supported by government initiatives and investments, aligning with the nation's economic diversification and sustainability goals.

Saudi Arabia is investing in and expanding desalination technology to provide about half of its drinking water, with a focus on energy-efficient methods to reduce environmental impact. Technologies are being developed for advanced wastewater treatment to make it suitable for reuse, contributing to the water supply and promoting a circular economy. The implementation of smart technologies like SCADA systems and smart meters is enabling more efficient monitoring, control, and distribution of water, helping to reduce leaks and optimise supply. Innovations in improving the efficiency of water transportation and storage are being explored to ensure a more secure and resilient water network.

The government is actively pursuing technological solutions as part of its national strategy, aligning water sustainability with economic growth and environmental goals, such as the Saudi Green Initiative. Significant investment is being channelled into developing and implementing new water technologies. For example, the issuance of green bonds supports projects in renewable energy and water reuse. Research is being conducted to address specific challenges, such as developing new catalysts for improving wastewater treatment plants. Alongside technological solutions, public awareness campaigns are crucial to promote water conservation among citizens and industries.

Thus, Saudi Arabia has progressed well in various activities related to water security. It is time now to assess how far and how well these initiatives have performed and the need for further initiatives. This research is an attempt in this direction.

2. LITERATURE REVIEW

This review will is divided into five parts, aligned with the objectives.

2.1 The current state of technological innovation adoption in Saudi Arabia

Technological innovation adoption in Saudi Arabia is advancing rapidly, driven by Vision 2030, but faces sector-specific challenges and varying adoption rates.

2.1.1 National and Sectoral Drivers, Enablers, and Barriers

Saudi Arabia's push for technological innovation closely aligns with its Vision 2030 goals, highlighting digital transformation in government, business, education, and energy sectors. Main drivers include strategic alignment with national development, operational efficiency, and increased accessibility. Essential enablers are strong regulatory frameworks, leadership commitment, and infrastructure readiness. Nevertheless, challenges remain, such as technical complexities (notably integrating legacy systems), financial limitations, and organisational resistance to change (Alshahrani, 2025; Albar & Hoque, 2019; Badghish & Soomro, 2024; Asiri et al., 2024; Wasiq et al., 2023; Ali & Salih, 2025).

Table 1. Adoption Trends Across Sectors

Sector	Key Technologies Adopted	Main Drivers/Barriers	Citations
Government	Digital platforms, e-services	Vision 2030, efficiency, regulatory support; legacy integration, resistance to change	(Alshahrani, 2025; Al-Ghaith et al., 2010)
SMEs	AI, big data, e-business, green innovation	Relative advantage, government support, market demand; resource limitations, need for training	(Badghish & Soomro, 2024; Asiri et al., 2024; Wasiq et al., 2023; Satar & Alarifi, 2022)
Education	IoT, e-learning, ICT	Usability, technical support, individual skills, financial and infrastructure barriers	(Ali et al., 2023; Alalwan et al., 2018; Masadeh & El-Haggar, 2023)
Energy	Renewable and solar technologies	Economic factors, education, environmental awareness, cost, age, and awareness gaps	(Mosly & Makki, 2018; Bouaguel & Alsulimani, 2022)
Finance	Fintech, digital banking	Financial inclusion, cost reduction, regulatory sandbox, cybersecurity, compliance	(Alnemer, 2022; Malik, 2025)
Agriculture	IoT for smart farming	Awareness, training, government support, and access to information	(Jabbari et al., 2023)
Logistics	RFID, supply chain tech	Management support, partner pressure, cost, and technical issues	(Mahdaly & Adeinat, 2022)

2.2 Key Factors Influencing Adoption

Perceived usefulness, ease of use, and trust are consistently significant for user adoption across digital services and platforms (Alalwan et al., 2018; Al-Ghaith et al., 2010; Alnemer, 2022; Bouaguel & Alsulimani, 2022).

Government support, regulatory environment, and leadership are crucial for organisational adoption, especially in SMEs and logistics (Alshahrani, 2025; Albar & Hoque, 2019; Badghish & Soomro, 2024; Wasiq et al., 2023; Mahdaly & Adeinat, 2022).

Financial and technical barriers remain significant, particularly for SMEs and in rural or less-developed sectors (Ali et al., 2023; Albar & Hoque, 2019; Asiri et al., 2024; Jabbari et al., 2023; Mahdaly & Adeinat, 2022).

Thus, Saudi Arabia is making substantial progress in adopting technological innovations, with strong government backing and a clear strategic direction. While adoption is robust in some sectors, others face persistent challenges related to resources, skills, and organisational culture. Addressing these barriers through targeted policies, investments, and capacity-building will be essential to realising the full potential of technological innovation in line with Vision 2030.

2.3 Key factors influencing the implementation of innovative water sustainability solutions in Saudi Arabia

The implementation of innovative water sustainability solutions in Saudi Arabia is shaped by five interrelated factors: water scarcity, technological capacity, policy frameworks, public awareness, and sectoral coordination.

2.3.1 Water Scarcity and Resource Management

Saudi Arabia's arid climate, limited renewable water resources, and heavy dependence on non-renewable groundwater underscore the urgency of sustainable water strategies. Agriculture alone consumes more than 80% of available water, making efficient irrigation and reuse practices indispensable. Climate change intensifies scarcity and variability, necessitating adaptive management and diversification of water sources, including desalination, treated wastewater, and rainwater harvesting (Alotaibi et al., 2023; Mir & Ashraf, 2023; Alodah, 2023; Sherif et al., 2023).

2.3.2 Technological Innovation and Capacity

Advanced technologies-such as IoT-enabled smart irrigation, remote sensing for demand management, and modern wastewater treatment-offer significant potential to enhance efficiency. Yet, adoption is constrained by high capital costs, limited technical expertise, and the need for resilient digital infrastructure and cybersecurity safeguards (Jabbari et al., 2024; Elkatoury & Alazba, 2024; Pawar et al., 2025; Haider et al., 2024; Maher et al., 2025).

2.3.3 Policy, Governance, and Economic Instruments

Successful implementation requires integrated water policies, regulatory reforms, and economic instruments such as water pricing and subsidy restructuring. Strong governance, inter-sectoral coordination, and alignment with national priorities-particularly Vision 2030-are critical. Public–private partnerships and circular economy approaches further strengthen the sustainability of infrastructure development (Alotaibi et al., 2023; Alodah, 2023; Mani & Goniewicz, 2023; Wasiq et al., 2023; Farooqi, 2025).

2.3.4 Public Awareness and Socioeconomic Factors

Public engagement through awareness campaigns, education, and community initiatives is essential to foster conservation-oriented behaviours. Socioeconomic dynamics-such as resistance to tariff increases and the need for culturally sensitive policy design-shape household and agricultural adoption of sustainable practices (Obeid, 2020; Almulhim & Abubakar, 2023; Alotaibi & Kassem, 2021; Almulhim & Abubakar, 2025; Baig et al., 2020).

2.3.5 Barriers and Challenges

Persistent challenges include fragmented policy implementation, inadequate data sharing, ageing infrastructure, and underutilization of treated wastewater. Overcoming these barriers requires holistic, multi-level strategies supported by continuous monitoring and evaluation (Obeid, 2020; Mir & Ashraf, 2023; Ghanim, 2019; Sherif et al., 2023).

Therefore, an effective realisation of innovative water sustainability solutions in Saudi Arabia depends on the integration of advanced technologies, coherent policy frameworks, active public participation, and coordinated action across sectors. Tailoring these efforts to the Kingdom's unique environmental and socioeconomic conditions will be pivotal in ensuring long-term resilience and sustainability.

2.4 Effectiveness of various technological innovations in improving water security in Saudi Arabia

Technological innovations have markedly strengthened water security in Saudi Arabia, with IoT-based systems, advanced desalination, wastewater reuse, and digital management tools demonstrating the greatest impact.

2.4.1 IoT-Based Water Management

Agriculture: IoT-enabled monitoring of soil moisture, weather, and irrigation has significantly improved water-use efficiency and crop yields. These systems reduce wastage and support sustainable agricultural practices (Baljon, 2023; Jabbari et al., 2024).

Urban/Residential: Smart IoT platforms detect leaks, monitor water quality, and automate supply, ensuring reliable, efficient, and cost-effective water distribution in residential settings (AlGhamdi & Sharma, 2022).

2.4.2 Advanced Desalination Technologies

Decentralised Desalination: Innovations such as adsorption–desorption desalination (ADD), when integrated with renewable energy, cut energy consumption by up to 65% compared to conventional methods, reducing both costs and environmental impacts (Alnajdi et al., 2020).

Reverse Osmosis: The shift from thermal to reverse osmosis desalination has enhanced water quality and operational efficiency, though careful monitoring remains necessary to manage by-products (Al-Hamzah & Fellows, 2024).

Wastewater Treatment and Reuse

Treated Wastewater: Expanded reuse for irrigation and urban landscaping has helped stabilise groundwater levels and reduce reliance on non-renewable sources. Projections indicate a 43.6% increase in reuse by 2035 (Alhajri et al., 2025; Hamed et al., 2024; Maher et al., 2025).

Technological Advances: Membrane filtration and advanced oxidation processes have improved the safety and applicability of recycled wastewater for agriculture and industry (Maher et al., 2025).

2.4.3 Digital and Smart Infrastructure

Smart Meters & Blockchain: Digital tools enhance transparency, operational efficiency, and public awareness, strengthening conservation and management practices (Pawar et al., 2025).

Remote Sensing and Data Analytics

Irrigation Optimisation: Remote sensing combined with machine learning enables precise estimation of plant water requirements, reducing irrigation demand by up to 70% in urban landscaping projects (Elkatoury & Alazba, 2024; Yassin et al., 2024).

Collectively, these innovations-particularly IoT-based management, advanced desalination, wastewater reuse, and digital monitoring-are proving highly effective in advancing water security in Saudi Arabia. Sustained integration of these technologies, supported by robust policies and active public engagement, will be critical to achieving long-term, sustainable water management in this arid region.

2.5 Barriers and enablers to innovation-driven water sustainability initiatives in Saudi Arabia

Saudi Arabia's pursuit of innovation-driven water sustainability is shaped by a complex interplay of barriers and enablers. While technical, institutional, and social challenges constrain progress, policy reforms, technological advancements, and collaborative partnerships are creating new opportunities for transformation.

2.5.1 Barriers to Innovation-Driven Water Sustainability

Technical and Financial Barriers: High upfront investment costs, limited technical expertise, and cybersecurity concerns restrict the widespread adoption of advanced solutions such as IoT-based smart irrigation and digital water management systems (Jabbari et al., 2024; Pawar et al., 2025; Madkhali & Sithole, 2023).

Institutional and Policy Gaps: Fragmented governance structures, weak inter-sectoral coordination, and inadequate enforcement of integrated water policies undermine holistic water management (Obeid, 2020; Alodah, 2023; Mani & Goniewicz, 2023; Almulhim & Al-Saidi, 2023).

Public Awareness and Social Acceptance: Limited understanding of circular economy principles and water-saving behaviours, coupled with societal resistance to recycled wastewater use, slows the uptake of innovative practices (Maher et al., 2025; Almulhim & Abubakar, 2021; Obeid, 2020).

Resource Constraints: Heavy dependence on non-renewable groundwater, significant losses in distribution networks, and scarcity of renewable water sources intensify sustainability challenges (Alotaibi et al., 2023; Alodah, 2023; Mir & Ashraf, 2023; Alotaibi & Kassem, 2021).

Enablers and Opportunities

Policy and Regulatory Support: National initiatives such as Vision 2030, subsidy reforms, and the introduction of green building codes and circular economy frameworks are driving efficiency and innovation in water use (Alodah, 2023; Almulhim & Al-Saidi, 2023; Farooqi, 2025; Hasanain & Nawari, 2022).

Technological Advancements: Expanding adoption of IoT, remote sensing, advanced wastewater treatment, and digital platforms is enhancing monitoring, conservation, and reuse capabilities (Jabbari et al., 2024; Elkatoury & Alazba, 2024; Pawar et al., 2025; Madkhali & Sithole, 2023).

Public-Private Partnerships (PPP): PPPs aligned with circular economy principles are enabling resource recovery, infrastructure investment, and sustainable project delivery (Farooqi, 2025; Almulhim & Al-Saidi, 2023).

Awareness and Capacity Building: Educational campaigns, community engagement, and academic involvement are strengthening public acceptance and building capacity for sustainable practices (Obeid, 2020; Alotaibi & Kassem, 2021; Almulhim & Abubakar, 2021).

Thus, Saudi Arabia's water sustainability agenda is constrained by technical, institutional, and social barriers, yet increasingly supported by enabling policies, advanced technologies, and collaborative partnerships. Bridging these divides-through integrated governance, capacity building, and continued innovation-will be essential to achieving resilient and sustainable water management in the Kingdom's arid environment.

Table 2. Barriers and Enablers Overview

Category	Barriers	Enablers	Citations
Technical/Financial	High costs, lack of expertise, and security issues	IoT, remote sensing, digital platforms	(Jabbari et al., 2024; Pawar et al., 2025; Elkatoury & Alazba, 2024; Madkhali & Sithole, 2023)
Institutional/Policy	Fragmented governance, weak enforcement	Vision 2030, green codes, circular economy policies	(Obeid, 2020; Alodah, 2023; Mani & Goniewicz, 2023; Almulhim & Al-Saidi, 2023; Hasanain & Nawari, 2022)
Social/Public Awareness	Low awareness, resistance to innovation	Education, community engagement	(Maher et al., 2025; Almulhim & Abubakar, 2021; Obeid, 2020; Alotaibi & Kassem, 2021)
Resource Constraints	Overuse of groundwater, water loss	Wastewater reuse, desalination, and PPPs	(Alotaibi et al., 2023; Alodah, 2023; Mir & Ashraf, 2023; Farooqi, 2025; Almulhim & Al-Saidi, 2023)

Thus, Saudi Arabia's path to water sustainability is challenged by technical, institutional, and social barriers, but is increasingly enabled by policy reforms, technological innovation, and collaborative frameworks. Addressing these barriers through integrated strategies and stakeholder engagement is essential for long-term water security and sustainability.

2.6 Policies and practices that can enhance water sustainability through innovation in Saudi Arabia

Enhancing water sustainability in Saudi Arabia requires a comprehensive approach that combines demand management, technology adoption, wastewater reuse, and integrated governance. Together, these strategies form the backbone of a resilient and sustainable water future.

2.6.1 Demand Management and Policy Integration

Demand-Side Efficiency: Managing demand is more sustainable than expanding supply, particularly in agriculture, which consumes over 80% of Saudi water resources (Alotaibi et al., 2023; Almulhim & Abubakar, 2023; Obeid, 2020).

Integrated Policy Frameworks: National policies should align water and agricultural strategies to improve input efficiency and productivity, supported by region-specific management plans (Alotaibi et al., 2023; Obeid, 2020).

Economic Instruments: Pricing reforms and subsidy reductions can incentivize conservation and encourage efficient water use (Alotaibi et al., 2023; Alodah, 2023).

2.6.2 Technological Innovation

Smart Irrigation: IoT-based irrigation and real-time monitoring systems enhance agricultural efficiency, reducing waste and boosting yields (Baljon, 2023; Jabbari et al., 2024).

Urban Optimisation: Remote sensing and evapotranspiration modelling, exemplified by the Green Riyadh initiative, optimises urban irrigation and can reduce water demand by up to 70% (Elkatoury & Alazba, 2024).

Wastewater Reuse Technologies: Investment in advanced treatment methods-such as membrane filtration and oxidation processes-supplements water supply and reduces dependence on non-renewable groundwater (Haider et al., 2024; Alhajri et al., 2025; Hamed et al., 2024; Maher et al., 2025).

2.6.3 Circular Economy and Resource Recovery

PPP-Driven Innovation: Aligning water projects with circular economy principles-resource recovery, waste minimisation, and reuse-through public-private partnerships fosters long-term sustainability (Farooqi, 2025; Almulhim & Al-Saidi, 2023).

Recycled Wastewater: Increasing recognition of recycled wastewater as a sustainable source for agriculture, industry, and even potable use highlights the need for supportive regulation and public acceptance (Maher et al., 2025; Alhajri et al., 2025; Hamed et al., 2024).

2.6.4 Governance, Awareness, and Capacity Building

Institutional Strengthening: Enhancing state agencies, improving regulatory frameworks, and fostering multi-sectoral collaboration are critical for effective governance (Alotaibi et al., 2023; Obeid, 2020; Alhajri et al., 2025).

Public Engagement: Awareness campaigns and education-particularly targeting youth-are essential to promote conservation and responsible water use (Alodah, 2023; Obeid, 2020; Alotaibi & Kassem, 2021).

Saudi Arabia’s water sustainability agenda depends on balancing demand-side efficiency with technological innovation, circular economy practices, and strong governance. By integrating these policies and practices, supported by public engagement and private-sector collaboration, the Kingdom can move toward a more resilient and sustainable water future.

Table 3: Innovative Practices and Policy Recommendations

Area	Example/Recommendation	Citations
Demand Management	Water pricing, integrated agri-water policy	(Alotaibi et al., 2023; Obeid, 2020; Alodah, 2023)
Technological Innovation	IoT irrigation, remote sensing, wastewater reuse	(Elkatoury & Alazba, 2024; Baljon, 2023; Jabbari et al., 2024; Haider et al., 2024)
Circular Economy	PPPs, resource recovery, water reuse	(Farooqi, 2025; Almulhim & Al-Saidi, 2023; Maher et al., 2025)
Governance & Awareness	Agency strengthening, public education	(Alotaibi et al., 2023; Obeid, 2020; Alhajri et al., 2025; Alotaibi & Kassem, 2021)

Saudi Arabia’s path to water sustainability relies on a combination of innovative technologies, integrated policies, circular economy approaches, and robust governance. Emphasising demand management, wastewater reuse, and public engagement will be crucial for long-term resilience and resource security.

3. METHODOLOGY

3.1 Research Design

This study employed a mixed-methods approach combining quantitative survey data with qualitative insights to examine the relationship between technological innovation and water sustainability in Saudi Arabia. The research was conducted between March and August 2024 across multiple regions of the kingdom.

3.2 Research Objectives

The primary objectives of this study were:

To assess the current state of technological innovation adoption in water management practices across Saudi Arabian institutions and industries

To identify the key factors influencing the implementation of innovative water sustainability solutions

To evaluate the perceived effectiveness of various technological innovations in improving water security

To examine the barriers and enablers to innovation-driven water sustainability initiatives

To develop recommendations for policy and practice to enhance water sustainability through innovation

3.3 Research Hypotheses

Based on the literature review and research objectives, the following hypotheses were formulated:

H1: There is a significant positive relationship between the level of technological innovation adoption and water sustainability outcomes.

H2: Organisational factors (size, resources, leadership support) significantly influence the adoption of innovative water technologies.

H3: Perceived usefulness and ease of use of water innovations are positively associated with their adoption rates.

H4: Regulatory support and policy frameworks moderate the relationship between innovation adoption and water sustainability outcomes.

H5: There are significant differences in innovation adoption patterns across different sectors (agricultural, industrial, municipal, and residential).

3.4 Study Population and Sampling

The target population consisted of water management professionals, agricultural sector representatives, industrial facility managers, municipal water authorities, and technology providers operating in Saudi Arabia. A stratified random sampling approach was employed to ensure representation across different sectors and regions.

Sampling Framework:

Total target population: Approximately 2,850 eligible participants

Required sample size (95% confidence level, 5% margin of error): 338 participants

Final sample achieved: 425 participants (response rate: 67.8%)

The sample was stratified across five sectors:

Agricultural sector (n=95, 22.4%)

Industrial sector (n=108, 25.4%)

Municipal water authorities (n=87, 20.5%)

Residential/community representatives (n=75, 17.6%)

Technology providers and consultants (n=60, 14.1%)

Regional distribution included: Central Region (Riyadh) 38%, Western Region (Jeddah, Makkah) 27%, Eastern Region (Dammam) 20%, and Northern/Southern Regions 15%.

3.5 Data Collection Instruments

3.5.1 Structured Questionnaire

A comprehensive questionnaire was developed, consisting of 68 items organised into seven sections:

Demographic and organisational characteristics (8 items)

Current water management practices (12 items)

Innovation adoption patterns (15 items) - measured using a 5-point Likert scale

Perceived benefits and barriers (13 items) - 5-point Likert scale

Water sustainability outcomes (10 items) - objective and subjective measures

Policy and regulatory environment (6 items)

Future intentions and recommendations (4 items)

The questionnaire was developed in both English and Arabic, with back-translation procedures employed to ensure linguistic equivalence.

3.5.2 Semi-Structured Interviews

In-depth interviews were conducted with 32 key stakeholders, including water authority directors, innovation managers, and policy makers, to gain deeper insights into the mechanisms and challenges of innovation implementation.

3.6 Pilot Study

A pilot study was conducted with 45 participants to test the reliability and validity of the instruments. Based on feedback, minor modifications were made in the survey questionnaire to improve clarity and cultural appropriateness.

3.7 Data Collection Procedure

Data collection occurred in three phases:

Phase 1 (March-April 2024): Distribution of online surveys through professional networks, industry associations, and government channels.

Phase 2 (May-June 2024): On-site surveys at industry conferences, water management facilities, and agricultural cooperatives.

Phase 3 (July-August 2024): Qualitative interviews with key stakeholders and follow-up surveys to improve response rates.

3.8 Validity and Reliability

Content validity was established through expert review by five water management and innovation specialists.

Construct validity was assessed using confirmatory factor analysis (CFA). All constructs demonstrated adequate convergent validity (AVE > 0.5) and discriminant validity.

Reliability was measured using Cronbach's alpha coefficients:

Innovation adoption scale: α = 0.89

Perceived benefits scale: α = 0.87

Barriers scale: α = 0.84

Water sustainability outcomes: α = 0.91

Overall instrument: α = 0.93

3.9 Data Analysis

Quantitative data were analysed using SPSS Version 28.0 and AMOS 26.0. The following statistical techniques were employed:

Descriptive statistics (frequencies, means, standard deviations)

Inferential statistics (t-tests, ANOVA, correlation analysis)

Multiple regression analysis to test hypothesised relationships

Structural equation modelling (SEM) to examine the overall theoretical model

Chi-square tests for categorical variable associations

Qualitative data from interviews were transcribed and analysed using thematic analysis in NVivo 14, employing both deductive and inductive coding approaches.

3.10 Ethical Considerations

The study received ethical approval from the Institutional Review Board (IRB Protocol #2024-WS-087). All participants provided informed consent, and confidentiality was maintained throughout the research process. Data were stored securely and anonymised for analysis.

4. RESULTS

4.1 Demographic Characteristics of Participants

Table 1 presents the demographic and organisational characteristics of the study participants.

Table 1: Demographic and Organisational Characteristics (N=425)

Characteristic	Category	Frequency	Percentage
Gender	Male	312	73.4%
	Female	113	26.6%
Age Group	25-35 years	142	33.4%
	36-45 years	168	39.5%
	46-55 years	89	20.9%
	56+ years	26	6.1%
Education Level	Bachelor's degree	189	44.5%
	Master's degree	176	41.4%
	Doctoral degree	60	14.1%
Years of Experience	< 5 years	98	23.1%
	5-10 years	147	34.6%
	11-20 years	134	31.5%
	> 20 years	46	10.8%
Organization Size	Small (< 50 employees)	87	20.5%
	Medium (50-250)	156	36.7%
	Large (> 250)	182	42.8%
Sector	Agricultural	95	22.4%
	Industrial	108	25.4%
	Municipal	87	20.5%
	Residential	75	17.6%
	Technology providers	60	14.1%

About 73% of the participants were male. About 94% of the participants were at or below 55 years of age. All were well-educated. Most of them (77%) had over five years of experience. Most of them (79%) worked in medium and large organisations. About 78% of them worked in non-agricultural sectors.

4.2 Current State of Innovation Adoption

The study assessed the adoption levels of various water sustainability innovations across the sample. Results indicate varying adoption rates across different technological categories.

Table 2: Adoption Rates of Water Sustainability Innovations

Innovation Category	Adopted (%)	Planning to Adopt (%)	Not Considering (%)	Mean Score*
Smart water metering systems	62.4%	24.7%	12.9%	3.89
Advanced desalination technologies	48.2%	31.5%	20.3%	3.42
Water recycling and reuse systems	71.3%	19.1%	9.6%	4.12
Drip irrigation/precision agriculture	68.9%	18.4%	12.7%	3.98
Leak detection AI systems	41.7%	33.2%	25.1%	3.28
Rainwater harvesting systems	55.8%	26.4%	17.8%	3.64
Atmospheric water generation	23.5%	28.9%	47.6%	2.71
Blockchain water trading platforms	18.6%	22.1%	59.3%	2.43
IoT-based water quality monitoring	52.7%	29.4%	17.9%	3.58
Solar-powered water solutions	64.5%	23.8%	11.7%	3.84

*Mean scores based on 5-point scale: 1=No plans to adopt, 5=Fully implemented

The three most adopted innovations were water recycling and reuse (71.3%), drip irrigation/precision agriculture (68.9%), and smart water metering systems (62.4%). The three most innovations planning to adopt were leak detection AI systems (33.2%), advanced desalination technologies (31.5%), and IoT-based water quality monitoring (29.4%). The three most innovations not considered were blockchain water trading platforms (59.3%), atmospheric water generation (47.6%), and leak detection AI systems (25.1%). Interestingly, leak detection AI systems were an innovation planned by many organisations, and at the same time, not considered by many other organisations. Mean scores of most innovations neared the adoption side (>3), except for atmospheric water generation (2.71) and blockchain water trading platforms (2.43).

4.3 Factors Influencing Innovation Adoption

Multiple regression analysis was conducted to identify factors predicting innovation adoption intensity (measured as a composite score of innovation implementation).

Table 3: Regression Analysis - Predictors of Innovation Adoption

Predictor Variable	B	SE	β	t	p	VIF
(Constant)	0.847	0.312	-	2.714	.007	-
Organizational size	0.234	0.067	.186	3.493	< .001	1.34
Leadership support	0.412	0.071	.327	5.803	< .001	1.52
Financial resources	0.298	0.065	.241	4.585	< .001	1.48
Technical expertise	0.327	0.069	.259	4.739	< .001	1.61
Perceived usefulness	0.389	0.074	.295	5.257	< .001	1.71
Ease of use	0.156	0.063	.128	2.476	.014	1.44
Regulatory support	0.267	0.059	.219	4.525	< .001	1.29
Competitive pressure	0.189	0.057	.154	3.316	.001	1.38

Model Summary: $R^2 = .682$, Adjusted $R^2 = .676$, $F(8, 416) = 111.47$, $p < .001$

All predictors significantly contributed to innovation adoption, with leadership support, perceived usefulness, and technical expertise showing the strongest effects.

4.4 Hypothesis Testing

H1: Relationship between innovation adoption and water sustainability outcomes

Pearson correlation analysis revealed a strong positive relationship between innovation adoption intensity and water sustainability outcomes ($r = .726$, $p < .001$). Linear regression confirmed that innovation adoption explained 52.7% of the variance in sustainability outcomes ($R^2 = .527$, $F(1, 423) = 472.38$, $p < .001$, $\beta = .726$).

Table 4: Innovation Impact on Specific Sustainability Metrics

Sustainability Metric	Low Innovation Adopters (n=142)	High Innovation Adopters (n=141)	t-value	p-value	Cohen's d
Water consumption reduction (%)	12.4 ± 6.7	31.8 ± 9.2	-19.84	< .001	2.37
Water efficiency improvement (%)	15.6 ± 7.3	38.4 ± 10.6	-20.42	< .001	2.45
Cost savings (% reduction)	8.9 ± 5.4	26.7 ± 8.9	-19.53	< .001	2.35
Water quality score (1-10)	6.2 ± 1.4	8.6 ± 1.1	-15.87	< .001	1.89
System reliability (% uptime)	78.3 ± 12.6	93.7 ± 6.4	-12.68	< .001	1.52

Result: H1 supported - Strong positive relationship confirmed.

H2: Organisational factors and innovation adoption

Hierarchical regression analysis demonstrated that organisational factors collectively explained 41.3% of variance in innovation adoption ($\Delta R^2 = .413$, $F(3, 421) = 98.46$, $p < .001$). Organization size ($\beta = .186$, $p < .001$), available resources ($\beta = .241$, $p < .001$), and leadership support ($\beta = .327$, $p < .001$) all showed significant positive effects.

Result: H2 supported - Organisational factors significantly influence adoption.

H3: Technology acceptance factors

Both perceived usefulness ($\beta = .295$, $p < .001$) and ease of use ($\beta = .128$, $p < .05$) were significant predictors of adoption intention. Mediation analysis showed that perceived usefulness partially mediated the relationship between organisational support and actual adoption (indirect effect = .187, 95% CI [.134, .246]).

Result: H3 supported - Technology acceptance factors are positively associated with adoption.

H4: Moderating effect of regulatory support

Moderation analysis revealed a significant interaction between innovation adoption and regulatory support in predicting sustainability outcomes ($\beta = .164$, $p < .01$). The relationship between innovation and outcomes was stronger under high regulatory support conditions (simple slope = .812, $p < .001$) compared to low regulatory support (simple slope = .584, $p < .001$).

Figure 1: Moderation Effect of Regulatory Support

```
Sustainability Outcomes
          ^
   10     |                    /—— High Regulato
          |                  /
    8     |                /
          |              /   /— Low Regulatory Su
    6     |            /   /
          |          /   /
    4     |        /   /
          |      /   /
    2     |    /   /
          |  /   /
    0     |/__/________________>
          Low    Mid    High
             Innovation Adoption Level
```

Result: H4 supported - Regulatory support moderates the innovation-sustainability relationship.

H5: Sectoral differences in innovation adoption

One-way ANOVA revealed significant differences across sectors ($F(4, 420) = 18.73$, $p < .001$, $\eta^2 = .151$). Post-hoc Tukey tests showed innovation adoption was strongest in the industrial sector after technology providers, followed by the municipal sector. The adoption score for the residential sector was lower than implementation levels (2.97).

Table 5: Innovation Adoption Scores by Sector

Sector	Mean	SD	Significantly Different From
Industrial	4.12	0.67	All except Municipal
Municipal	3.89	0.74	Agricultural, Residential
Agricultural	3.54	0.82	Industrial, Municipal, Technology
Technology Providers	4.38	0.59	All sectors
Residential	2.97	0.91	All sectors

Result: H5 supported - Significant sectoral differences exist in adoption patterns.

4.5 Barriers to Innovation Adoption

Participants rated various barriers to innovation adoption. Results are presented in descending order of perceived severity.

Table 6: Barriers to Innovation Adoption (Scale: 1=Not a barrier, 5=Major barrier)

Barrier	Mean	SD	% Rating as Major Barrier
High initial capital costs	4.26	0.83	68.2%
Lack of technical expertise	3.94	0.91	54.8%
Insufficient financial incentives	3.87	0.95	51.3%
Regulatory complexity/uncertainty	3.76	1.02	47.1%
Resistance to change in organisation	3.68	0.98	44.5%
Limited awareness of available technologies	3.54	1.04	39.8%
Inadequate infrastructure	3.49	1.08	37.2%
Lack of government support	3.42	1.11	35.6%
Technology compatibility issues	3.31	0.97	31.8%
Uncertain return on investment	3.28	1.06	30.4%
Water pricing structures	3.15	1.14	27.3%
Lack of demonstration projects	2.97	1.09	22.1%

The top three barriers were high initial capital costs, lack of expertise and insufficient financial incentives.

4.6 Perceived Benefits of Innovation

Table 7: Perceived Benefits of Water Sustainability Innovations

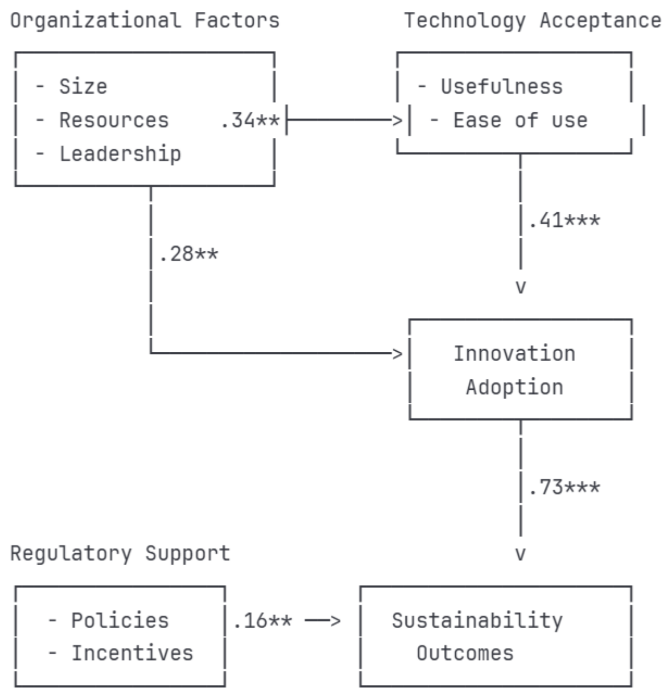
Benefit	Mean	SD	% Rating as Highly Beneficial
Reduced water consumption	4.52	0.68	82.6%
Improved water efficiency	4.48	0.71	80.9%
Long-term cost savings	4.31	0.79	74.4%
Enhanced water security	4.28	0.82	72.7%
Better environmental outcomes	4.24	0.77	71.3%
Improved system reliability	4.19	0.84	68.9%
Enhanced monitoring capabilities	4.07	0.88	63.5%
Competitive advantage	3.94	0.96	57.2%
Regulatory compliance	3.89	0.91	54.8%
Improved brand reputation	3.76	1.02	49.6%

The top four benefits were reduced water consumption, improved water efficiency, long-term savings and enhanced water security.

4.7 Structural Equation Modelling Results

A comprehensive structural model was tested to examine the relationships among organisational factors, technology acceptance, innovation adoption, and sustainability outcomes.

Figure 2: Structural Equation Model Results



Model Fit: $\chi^2/df = 2.34$, CFI = .961, TLI = .954, RMSEA = .056, SRMR = .048

$^{**}p < .01$, $^{***}p < .001$

Model fit indices indicated excellent fit. All hypothesised paths were significant and in the expected directions.

4.8 Qualitative Findings

Thematic analysis of 32 interviews revealed five major themes:

Theme 1: Innovation as Strategic Necessity Participants emphasised that innovation is no longer optional but essential for water security. One industrial manager stated: "With our current water challenges, innovation isn't just about efficiency-it's about survival."

Theme 2: The Implementation Gap Many participants described a gap between awareness and implementation, primarily due to financial and technical constraints. A municipal director noted: "We know what technologies exist, but bridging that gap to actual implementation requires resources we often don't have."

Theme 3: Importance of Demonstration and Peer Learning. Successful case studies and peer examples were repeatedly mentioned as critical factors. An agricultural cooperative leader explained: "Seeing a neighbouring farm successfully implement drip irrigation convinced more farmers than any government bulletin could."

Theme 4: Need for Integrated Policy Approach. Stakeholders called for comprehensive policy frameworks that combine incentives, regulations, and capacity building. A policymaker stated: "Piecemeal approaches don't work-we need integrated policy that addresses finance, training, and regulatory barriers simultaneously."

Theme 5: Cultural and Behavioural Dimensions Several participants highlighted that technology alone is insufficient without behavioural change and cultural acceptance. A community representative observed: "Technology is only half the solution; changing how people think about water is equally important."

4.9 Regional Variations

Analysis of regional differences revealed interesting patterns:

Table 8: Innovation Adoption by Region

Region	Mean Adoption Score	Key Innovation Focus	Primary Challenge
Central (Riyadh)	3.94 ± 0.71	Smart metering, recycling	High demand growth
Western (Jeddah)	3.82 ± 0.78	Desalination, quality monitoring	Energy costs
Eastern (Dammam)	4.08 ± 0.68	Industrial efficiency, reuse	Industrial complexity
Northern/Southern	3.41 ± 0.86	Agricultural innovation, rainwater	Limited infrastructure

ANOVA: $F(3, 421) = 12.47$, $p < .001$

4.10 Return on Investment Analysis

Participants who had implemented innovations for more than two years reported on financial returns:

Table 9: Reported ROI from Water Innovations (n=187)

ROI Category	Percentage of Respondents	Average Payback Period
Negative ROI (loss)	8.6%	N/A
Break-even (0-10% return)	14.4%	7-10 years
Moderate ROI (10-25%)	31.0%	4-6 years
Good ROI (25-50%)	28.3%	2-4 years
Excellent ROI (>50%)	17.6%	< 2 years

Mean reported ROI: 28.4% ± 19.7% Mean payback period: 4.2 ± 2.6 years. Thus, a majority of them (77%) enjoyed moderate to excellent ROI with 2 to 6 years of payback period.

4.11 Future Adoption Intentions

Participants indicated strong intentions to expand innovation adoption:

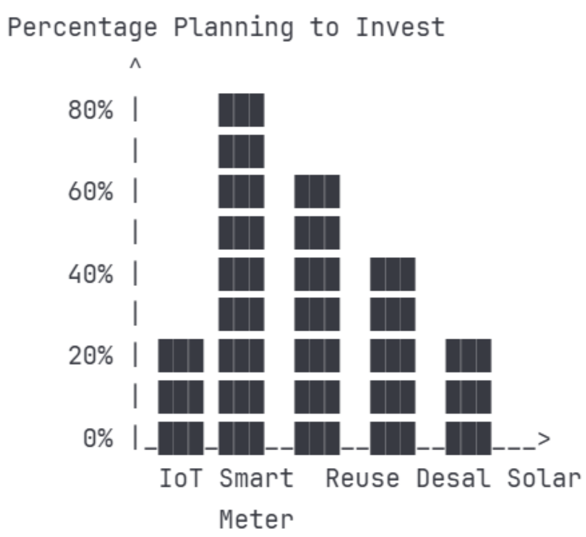
76.2% plan to adopt at least one new water innovation within the next 2 years

42.8% plan to significantly increase investment in water technologies

68.5% expressed interest in collaborative innovation projects

54.1% indicated willingness to participate in government pilot programs

Figure 3: Planned Innovation Investments (Next 3 Years)



Smart metering, reuse and desalination topped the list of innovations being planned to invest.

4.12 Summary of Key Findings

Water recycling systems and precision agriculture showed the highest adoption rates (71.3% and 68.9% respectively)

Innovation adoption strongly predicted sustainability outcomes ($r = .726$, $p < .001$)

Leadership support emerged as the strongest predictor of adoption ($\beta = .327$)

High-innovation adopters achieved 2-3 times better performance across all sustainability metrics

All five hypotheses were supported by the data

Significant sectoral differences exist, with technology providers and industrial sectors leading adoption

High initial costs remain the primary barrier (68.2% rated it as major)

Regulatory support significantly moderates innovation effectiveness

Most innovations demonstrate positive ROI within 4-6 years

Strong future adoption intentions indicate growing momentum

5. DISCUSSION

5.1 Most widely adopted water security innovations

The findings showed that the three most widely adopted water innovations are wastewater recycling and reuse, drip irrigation/precision agriculture, and smart water metering. Wastewater treatment and reuse form the cornerstone of the Kingdom's water strategy, with treated effluent increasingly deployed in agriculture, landscaping, and industry. The government has set an ambitious target to raise water reuse from 17% in 2016 to 70% by 2030, underscoring its central role in sustainability and water security (Ali et al., 2022; Alhajri et al., 2025; Maher et al., 2025; Kajenthira et al., 2012; Mohorjy, 1988). A major policy focus is the conversion of existing wastewater treatment plants into resource recovery facilities, advancing the circular economy and reducing dependence on desalination (Ali et al., 2022; Alhajri et al., 2025; Maher et al., 2025).

To address water scarcity and enhance agricultural productivity, Saudi Arabia promotes drip irrigation and precision agriculture. Techniques such as partial root-zone drying and regulated deficit irrigation have demonstrated significant water savings while maintaining or even boosting crop yields (Jabbari et al., 2024; Almahmoud & Attar, 2023; Jabbari et al., 2023; Alotaibi & Kassem, 2021; Alomran & Louki, 2024; Al-Omran et al., 2020). The uptake of IoT-enabled smart irrigation systems is growing, though challenges persist in terms of technical expertise and upfront investment costs (Jabbari et al., 2024; Almahmoud & Attar, 2023; Jabbari et al., 2023; Hamid et al., 2025).

Meanwhile, smart water metering and IoT-based water management systems are being rolled out across residential and agricultural sectors. These technologies enable real-time monitoring, leak detection, and optimised water use, directly supporting the sustainability objectives of Saudi Vision 2030 (AlGhamdi & Sharma, 2022; Pawar et al., 2025; Gupta et al., 2020; Li & Chong, 2019; Palermo et al., 2022). Smart meters and digital platforms are increasingly recognised for their role in enhancing operational efficiency and strengthening conservation efforts (AlGhamdi & Sharma, 2022; Pawar et al., 2025; Gupta et al., 2020; Li & Chong, 2019; Palermo et al., 2022).

Together, these innovations-water recycling and reuse, precision irrigation, and smart metering-are pivotal to Saudi Arabia's response to water scarcity. They improve efficiency, reinforce sustainability, and are progressively embedded into national strategies and infrastructure. Yet, scaling up adoption and raising public awareness remain essential to maximising their long-term impact.

5.2 Innovations being planned to adopt

The study showed that innovations that most organisations are planning to adopt were leak detection AI systems (33.2%), advanced desalination technologies (31.5%), and IoT-based water quality monitoring (29.4%).

AI-powered leak detection tools, such as the Smart Ball system, are being deployed to identify otherwise invisible leaks in underground pipelines, thereby reducing water loss and operational costs. These systems employ sensitive audio sensors and real-time analytics to detect and localise leaks, enabling rapid intervention and minimising waste (Alghadeer, 2023; Rajan & Li, 2025; Rojek & Studzinski, 2019). Automated leak management, integrating flow and pressure data with real-time alerts, is increasingly recognised as a cornerstone of smart water management (Rajan & Li, 2025; Rojek & Studzinski, 2019).

Saudi Arabia is also investing heavily in advanced desalination technologies, including solar photovoltaic-powered reverse osmosis (RO) and adsorption desorption desalination (ADD). These approaches deliver high salt rejection rates, lower energy consumption, and reduced carbon emissions compared to conventional thermal methods (El-Kawi, 2025; Alnajdi et al., 2020; Ghaffour et al., 2014; Alotaibi et al., 2023; Al-Hamzah & Fellows, 2024). The ongoing transition from thermal desalination to RO and hybrid renewable-powered systems reflects a national commitment to energy efficiency and environmental sustainability (Alnajdi et al., 2020; Ghaffour et al., 2014; Alotaibi et al., 2023; Al-Hamzah & Fellows, 2024).

At the same time, IoT-enabled water quality monitoring systems are being introduced across residential, agricultural, and industrial sectors. Equipped with sensors to track parameters such as pH, turbidity, and contaminants, these systems provide continuous, real-time data and issue alerts when water quality falls below standards (AlGhamdi & Sharma, 2022; Iftikhar & Bamarouf, 2025; Almahmoud & Attar, 2023; Pasika & Gandla, 2020; Essamlali et al., 2024; Hemdan et al., 2023). Enhanced by machine learning and cloud-based analytics, they support predictive capabilities, proactive management, and public health protection (AlGhamdi & Sharma, 2022; Iftikhar & Bamarouf, 2025; Essamlali et al., 2024; Hemdan et al., 2023).

In sum, Saudi Arabia's adoption of AI leak detection, advanced desalination, and IoT-based water quality monitoring reflects a strategic effort to tackle water scarcity, boost efficiency, and advance sustainability. These innovations are tightly aligned with national goals for resource management and environmental stewardship.

5.3 Innovations not considered

In this study, the three most innovations not considered were blockchain water trading platforms (59.3%), atmospheric water generation (47.6%), and leak detection AI systems (25.1%).

Saudi organisations continue to face significant water management challenges, yet blockchain water trading platforms, atmospheric water generation, and AI-based leak detection systems remain underutilised or confined to early adoption stages.

Blockchain-based water trading is widely recognised for its potential to deliver secure, transparent, and efficient resource management. However, in Saudi Arabia-as globally-the technology has yet to move beyond theoretical promise into practical, real-time applications (Satilmisoglu et al., 2024; Buyssens & Viaene, 2024; Liu & Shang, 2022; Pawar et al., 2025). Key barriers include limited empirical evidence, regulatory uncertainty, and difficulties integrating with existing infrastructure (Satilmisoglu et al., 2024; Pawar et al., 2025).

Atmospheric water generation (AWG) has demonstrated technical feasibility in Saudi Arabia's arid regions, with pilot devices showing promise for remote and emergency applications (Elashmawy & Alshammari, 2020; Elashmawy, 2020; Elashmawy & Alatawi, 2020; Li et al., 2020; Ejeian & Wang, 2021). Despite encouraging results, AWG systems remain immature and sparsely deployed. Large-scale, cost-effective implementation will require further research, technological refinement, and investment (Elashmawy & Alshammari, 2020; Elashmawy, 2020; Ejeian & Wang, 2021).

AI and IoT-enabled leak detection systems are recognised as effective tools for reducing water loss, yet adoption in Saudi Arabia is constrained by infrastructure limitations, data availability, and technical expertise (Alghadeer, 2023; Mahmoud et al., 2025; AlGhamdi & Sharma, 2022; Alsumayt et al., 2023). Current deployments are largely at pilot or early adoption stages, with broader implementation dependent on sustained investment and capacity building (Alghadeer, 2023; AlGhamdi & Sharma, 2022).

In sum, while Saudi Arabia acknowledges the potential of blockchain trading, atmospheric water generation, and AI-driven leak detection, these innovations remain in research, pilot, or early adoption phases. Their widespread implementation is hindered by technical, regulatory, and infrastructural barriers, underscoring the need for greater investment, empirical validation, and policy support to unlock their full benefits for sustainable water management.

5.4 Predictors of water security innovations in Saudi Arabia

In this study, all predictors significantly contributed to innovation adoption, with leadership support, perceived usefulness, and technical expertise showing the strongest effects. The importance of practising water-saving technologies in agriculture for water security in Saudi Arabia was stressed by Yusuf, Kooli, Khoj, and Bajnaid (2025). Vellaiyan, Chinthapalli, and Bandu (2025) noted that effective policy responses, such as improved land use regulation, investment in climate-resilient infrastructure, sustainable water governance frameworks, and public education campaigns, are essential to enhance long-term water security aligned with the water-related goals of Saudi Arabia's Vision 2030. According to Mahmood, Asghar, Rehan, and Maqbool (2024) Saudi Arabia is advancing from traditional farming to smart agriculture through government-led strategies and institutional reforms, leadership, behavioural readiness, and technological adaptation, collectively shaping Saudi Arabia's sustainable agricultural agenda. Thus, there is some support for the findings of this study on predictors.

5.5 Relationship between innovation adoption and water sustainability outcomes

Correlations showed a strong positive relationship between innovation adoption intensity and water sustainability outcomes. Linear regression confirmed that innovation adoption explained 52.7% of the variance in sustainability outcomes. A bibliometric literature review by Boros, Gordos, and Tőzsér (2024) showed that green innovation in the agricultural sector is essential for sustainable water management. A study by Nyiwul (2023) found that the affordability of innovative technologies for household wastewater reuse was constrained by income and utility levels of such services in the African countries. Institutional agents have a crucial role in the water innovation chain and provide insights to policymakers in water-stressed countries concerned about water management, especially in relation to potential interventions that promote and enhance improvements in wastewater management. Neves, Oliveira, and Santini (2022) observed from a meta-analysis of 44 papers and 48 datasets that attitude, benefits, personal norms, incentives, and perceived behavioural control are the best predictors of behavioural intention to adopt sustainable technologies. These findings provide some support for this study's findings.

5.6 Organisational factors and innovation adoption

In this study, organisational factors collectively explained 41.3% of the variance in innovation adoption. Organisation size, available resources, and leadership support all showed significant positive effects. Leadership support was one of the organisational factors for employee innovation adoption in the survey studies of Oeij, Hulsegge, and Preenen (2022). A systematic review and narrative synthesis by Alblooshi, Shamsuzzaman, and Haridy (2021) showed that leadership styles affected innovation adoption in organisations. An in-depth study of the UAE public organisations by Ashok, Al Dhaheri, Madan, and Dzandu (2021) showed that transformational leadership encourages knowledge creation and management. From a systematic review, Lins, Zotes, and Caiado (2021) noted a synergy between the critical success factors (CSFs) of innovation in services and the CSFs of lean initiatives. The selected factors included various organisational aspects, people management, processes and customer. From a survey of 101 humanitarian organisations in Uganda, Mutebi, Muhwezi, Ntayi, and Kigozi Munene (2020) found that organisational innovativeness was related to its size. Based on a survey of 123 Malaysian SMEs, Cheah, Leong, and Fernando (2023) observed that smaller companies might concentrate their scarce resources on process innovation with instant beneficial potential instead of a sophisticated marketing strategy. Based on 14 interviews with co-founders or top managers of five small firms in Iran, Karami, Hossain, Ojala, and Mehrara (2024) noted that small firms adopt technologies to access and mobilise social, human, psychological and financial resources in a highly uncertain environment to co-create new opportunities. A survey of 512 senior IT/IS managers in public/private organisations located in Jordan by Horani, et al. (2025) indicated that relative advantage, top management support, cost-effectiveness, competitive pressure, vendor support, compatibility, AI strategic alignment and availability of resources positively influence the intention to adopt AI-based technologies. Thus, the findings obtained in the study have good literature support.

5.7 Technology acceptance factors for innovation adoption

Both perceived usefulness and ease of use were significant predictors of adoption intention. Mediation analysis showed that perceived usefulness partially mediated the relationship between organisational support and actual adoption. Most works from Saudi Arabia deal with solar energy, other renewable energies and green energy adoption. For example, Bouaguel and Alsulimani (2022) found that perceived usefulness and perceived ease of use, relative advantages, environmental awareness, and cost of solar photovoltaic systems impacted the attitude of 492 survey respondents to solar energy use in their houses. Albaroudi, et al. (2025) discussed how AI innovations help sustainable water management in Saudi Arabia. It enables continuous monitoring and accurate prediction of the quality and quantity of water availability for proactive optimisation of usage. By providing spatial and temporal data, they help adaptive water management. Collaborative governance frameworks and robust public–private partnerships are vital to ensure technological solutions align with societal values and foster sustained engagement. Integrating AI-driven approaches into national strategies such as Vision 2030 strengthens environmental preservation, promotes economic resilience, and supports compliance with international sustainability commitments. These factors can be considered as perceived usefulness. However, key challenges include safeguarding data quality, addressing ethical and regulatory considerations, and enhancing users' technical capacity. A survey of 618 households in Dammam city by Almulhim and Abubakar (2025) revealed socioeconomic factors as significant predictors of garden management but not water conservation practices. The participants liked public awareness campaigns to promote water conservation practices. These factors can be considered as ease-of-use factors. Thus, there is indirect support from the literature for the findings of this study.

5.8 Moderating effect of regulatory support for innovation adoption

Moderation analysis in this study revealed a significant interaction between innovation adoption and regulatory support in predicting sustainability outcomes. The relationship between innovation and outcomes was stronger under high regulatory support conditions compared to low regulatory support. Regulatory support for sustainable water use and conservation in Saudi Arabia was advocated by Almulhim and Abubakar (2023). Based on four case studies, Madkhali and Sithole (2023) emphasised the crucial need for the government to focus on building digital capacity and removing technological barriers to ensure the widespread adoption of sustainable practices, suggesting a regulatory role in technology innovation. Pawar, Alharbi, Aldawish, and Alanazi (2025) Highlighted the importance of robust regulatory frameworks to manage innovation, to ensure sustainable development and prevent water stress reduction in Saudi Arabia, suggesting the necessity of regulatory support for innovation adoption. Thus, the role of regulatory support for innovation adoption has been stressed by many authors. These observations directly support the findings of this study.

5.9 Sectoral differences in innovation adoption for water security in Saudi Arabia

One-way ANOVA revealed significant differences across sectors. Post-hoc Tukey tests showed innovation adoption was strongest in the industrial sector after technology providers, followed by the municipal sector. The adoption score for the residential sector was lower than implementation levels. According to Abdelbaki (2025), the industrial sector consumes the highest quantity of water in Saudi Arabia, as it has a high water demand. The possibility of reusing treated wastewater in industry and the agricultural sector's use of treated municipal wastewater for irrigation, backed by a sectoral tariff system, was explored by Dawoud, Ewea, and Alaswad (2022). According to Ahmed, Johnson, Hashaikeh, and Hilal (2023) sectoral differences in innovation for water treatment arise due to differences in innovation financing, risk perceptions due to public health issues, payback periods and initial costs. Thus, some evidence for sectoral differences in water consumption exists. Similar differences in innovation adoption in different sectors can be found.

5.10 Barriers to innovation adoption for water security in Saudi Arabia

In this study, the top three barriers were high initial capital costs, lack of expertise and insufficient financial incentives. Maher, Antar, Alshrari, and Ali (2025) noted that incentives are required for the private and public sectors to finance their high initial capital costs for innovation for wastewater reuse strategies and consumption security in arid regions. According to Alotaibi, Baig, Najim, Shah, and Alamri (2023), the excessive reliance on non-sustainable groundwater over-pumping and energy-intensive desalination are current barriers to sustainable water use in Saudi Arabia. Ahmed, Johnson, Hashaikeh, and Hilal (2023) pointed out the policy and management barriers of low water pricing, regulatory restrictions, lack of incentives, limited funding, and industry fragmentation for water innovation. Also, there are industry adoption challenges of risk aversion due to public health concerns, the long lifetime and costs of current water infrastructure, and low financing are contributing factors to the water industry's slow adoption of innovative techniques. Thus, apart from the barriers identified in this study, other barriers also exist.

5.11 Perceived benefits of water sustainability innovations in Saudi Arabia

The top four benefits were reduced water consumption, improved water efficiency, long-term savings and enhanced water security. Alresheedi, et al. (2023) tested the sustainability of a low-cost ceramic filter bioreactor-type decentralised wastewater treatment system (DWWTS) for a small community of 1300 residents (160 households) in Qassim (KSA). The authors found that residents' knowledge about the environment and resource conservation resulted in a moderately high willingness to reuse treated effluent and WTA the decentralised system. The study also showed that the economic viability of a DWWTS remained at a moderate performance level due to a low monthly waste disposal cost. A survey of 624 households in the Dammam Metropolitan Area by Mu'azu, Abubakar, and Blaisi (2020) showed that the likelihood of a household to accept reusing treated mixed wastewater is influenced by gender, residential location, age and educational level, with a tendency for more acceptance of treated grey wastewater than mixed wastewater. However, sustainably meeting the country's rising water demands requires the stringent implementation of a strategic wastewater reuse policy, including bold steps towards wastewater streams segregation, and intensive public awareness campaigns to change negative perceptions on treated sewage effluent. A survey of 500 Saudi farmers by Jabbari, et al. (2023) showed that the participants perceived many benefits of using IoT for crop monitoring. These benefits are real-time monitoring, in which IoT sensors provide farmers with continuous data on soil moisture, temperature, humidity, and other environmental factors. Access to real-time information supports informed decisions on irrigation, fertilisation, and pest control, improving crop health and resource efficiency; proactive management, which results from continuous monitoring for early detection of anomalies; automated alerts or system-triggered interventions like adjusting irrigation schedules allow farmers to mitigate risks promptly and prevent crop damage; and yield prediction and planning possible by combining sensor data with machine-learning analysis, IoT systems forecast yield potential. These insights support effective harvesting, storage, and marketing strategies, while also strengthening financial planning and resource allocation. Thus, there are many benefits of water sustainability innovations in Saudi Arabia.

5.12 Qualitative findings

Innovation adoption is vital for Saudi Arabia's water sustainability, given its absence of permanent rivers and reliance on energy-intensive desalination. Technological advances improve efficiency in desalination and agriculture, reducing both energy and water consumption. At the same time, they foster economic diversification and resilience by positioning the Kingdom as a hub for water technology. Crucially, innovations are needed to meet rising water demand from population growth and industry, safeguard food security, and preserve scarce groundwater resources for future generations. It has importance for the environment, economy, society and the government.

Despite widespread recognition of water scarcity, many in Saudi Arabia lack a strong sense of obligation toward conservation. This gap is reinforced by a pricing system that fails to reflect the true cost of supply, limiting incentives for behavioural change. Infrastructure challenges further compound the issue, including underutilization of treated wastewater and incomplete household connections. These shortcomings persist despite government initiatives such as the National Water Strategy 2030, which seeks to strengthen demand management and modernise infrastructure.

Saudi Arabia requires comprehensive, integrated policies that combine incentives, regulations, and capacity building to address its acute water scarcity. The Kingdom's heavy reliance on costly desalination and non-renewable groundwater, coupled with high agricultural consumption and fragmented policies, underscores the urgency of reform. A unified strategy is essential to manage demand, expand reuse and recycling, accelerate adoption of water-efficient technologies, and strengthen public awareness-ensuring long-term water security and sustainability. There is a significant demand-supply gap. Agriculture is one of the heavy-consuming sectors. An integrated policy framework consists of incentives, regulations and capacity building. The benefits are enhanced sustainability, economic feasibility, improved water governance and climate change adaptation.

Demonstrations and peer learning are vital for promoting responsible water use in Saudi Arabia, offering practical, hands-on experience and reinforcing conservation as a social norm in a water-scarce context. These approaches effectively bridge the attitude–behaviour gap, where awareness of scarcity does not always translate into daily practice. By complementing top-down awareness campaigns with bottom-up, community-driven initiatives, they foster lasting behavioural change and strengthen the impact of official water policies. Demonstrations provide hands-on learning, skill building, engagement and behavioural change. Peer learning creates social norms, addresses attitudes, inspires action and empowers.

The cultural and behavioural aspects of water conservation in Saudi Arabia are multifaceted. Water is often perceived as a luxury, contributing to high consumption despite scarcity. A notable gap exists between acknowledging the need for conservation and feeling personally responsible to act. Household practices, cultural norms, and demographic factors such as age and gender further shape behaviours, influencing conservation outcomes in diverse ways. Cultural and perceptual dimensions are a luxury associated with unlimited water consumption, perceptions about personal obligations, and awareness vs. behaviour. Behavioural dimensions are habits and equipment, and some demographic factors. Influencing factors are household characteristics, socioeconomic factors, behavioural factors, effective strategies and policies.

5.13 Regional variations in innovation adoption for water sustainability in Saudi Arabia

Regional differences in water sustainability innovation in Saudi Arabia reflect variations in water sources, socioeconomic factors, and climate. Coastal areas focus on advanced desalination technologies, while the southwest region concentrates on improved management of surface and groundwater. In contrast, arid inland zones aim to boost efficiency to deal with limited resources. Socioeconomic disparities-especially in income and education-also influence household water-saving habits, with wealthier households often less inclined to adopt conservation measures. These differences are reflected in the findings of this study.

5.14 ROI from water innovations in Saudi Arabia

This study showed that a majority of the organisations (77%) enjoyed moderate to excellent ROI with a 2 to 6 years of payback period. The return on investment (ROI) from Saudi water innovations is substantial, driven by extreme water scarcity and ambitious Vision 2030 targets, including 90% wastewater reuse. Massive government spending-billions invested in projects such as NEOM-has catalysed booming markets in smart water management, desalination, and wastewater treatment. These innovations promise significant returns through cost savings, resource efficiency, and new revenue streams from treated water reuse in irrigation and industry. However, challenges remain, particularly high operating expenditures and skills gaps. Priority areas include AI- and IoT-enabled efficiency, advanced filtration technologies, and integrated energy–water systems, with several emerging solutions already demonstrating notable cost reductions. The key drivers are wastewater reuse, smart water management, advanced desalination and energy integration and smart cities projects like NEOM. The water treatment market is projected to reach over $7 billion by 2033; Smart Water Management is valued at $1.2B, and AI for water at $180M. Recent projects in Jazan alone were valued at over $1.2 billion, showing direct investment in innovation. Studies show integrated systems can cut energy costs (e.g., 17-19% in cooling), while advanced RO systems offer high water output at lower energy per cubic meter. There are investment opportunities in technology, infrastructure and services. These encouraging results have motivated the majority of organisations to expand their innovation adoption in various ways, as this study's findings show.

6. CONCLUSION

This comprehensive study demonstrates that technological innovation is fundamental to achieving water sustainability in Saudi Arabia, with strong empirical evidence supporting the positive relationship between innovation adoption and water security outcomes. The research confirms that water recycling systems, precision agriculture, and smart metering represent the most widely adopted innovations, collectively contributing to significant improvements in water consumption reduction, efficiency gains, and cost savings.

The findings reveal that successful innovation adoption requires a multifaceted approach combining strong leadership support, adequate financial resources, technical expertise, and supportive regulatory frameworks. Organizations demonstrating high innovation adoption achieved 2-3 times better performance across all sustainability metrics compared to low adopters, validating the strategic importance of technological investment in water management.

However, significant barriers persist, particularly high initial capital costs, lack of technical expertise, and insufficient financial incentives. The study identifies critical implementation gaps between awareness and actual deployment, highlighting the need for demonstration projects, peer learning mechanisms, and integrated policy approaches that simultaneously address financial, technical, and regulatory constraints.

Sectoral analysis reveals important variations in adoption patterns, with industrial and technology sectors leading while residential adoption lags. Regional differences reflect varying water challenges and socioeconomic contexts, necessitating tailored intervention strategies.

The strong future adoption intentions (76.2% planning new innovations within two years) and positive ROI outcomes (77% achieving moderate to excellent returns within 2-6 years) indicate growing momentum toward innovation-driven water sustainability. To maximize impact, Saudi Arabia must integrate technological solutions with behavioural change initiatives, strengthen governance frameworks, enhance public-private partnerships, and align innovation strategies with Vision 2030 objectives. These evidence-based recommendations provide a roadmap for other water-scarce regions pursuing sustainable water management through technological advancement

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