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Modern Technologies for Strengthening Water and Food Security: Insights from Leading International Experiences

Su ve Gıda Güvenliğinin Güçlendirilmesinde Modern Teknolojiler: Öncü Uluslararası Deneyimlerden Çıkarımlar

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Abstract

Water scarcity, climate variability, population growth, environmental degradation, and rising food demand increasingly threaten the capacity of countries to secure reliable water supplies and sustainable food production. These interconnected challenges are particularly significant in arid and semi-arid regions, where agricultural activity depends heavily on limited and increasingly uncertain water resources. This study examines the role of modern technologies in strengthening water and food security through an analytical review of selected leading international experiences. It first clarifies the concepts of modern technology, water security, and food security and then analyzes technological applications that support the rational and sustainable management of water resources and agricultural development. The study employs a descriptive–analytical approach based on conceptual literature, documentary evidence, and comparative examination of international practices. The analysis covers weather-modification and drought-management technologies, wastewater treatment and reuse, seawater desalination, evaporation-control techniques, water-efficient irrigation, and other innovations designed to increase water availability or reduce water losses. The findings indicate that modern technologies can contribute substantially to water sustainability by diversifying supply, improving resource efficiency, enabling the reuse of non-conventional water sources, and strengthening agricultural resilience. Their contribution to food security arises primarily through more reliable irrigation,

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improved water productivity, reduced exposure to drought, and greater continuity of agricultural production. However, technology alone cannot ensure sustainable outcomes. Its effectiveness depends on institutional capacity, appropriate regulation, financing, technical expertise, maintenance, environmental assessment, and adaptation to local conditions. The study concludes that developing countries, particularly those in North Africa, should incorporate appropriate technologies into integrated water and agricultural policies while strengthening research capacity, regional cooperation, technology transfer, and human-resource development.

Keywords: modern technology; water security; food security; wastewater reuse; seawater desalination; sustainable agriculture

Özet

Su kıtlığı, iklim değişkenliği, nüfus artışı, çevresel bozulma ve yükselen gıda talebi, ülkelerin güvenilir su kaynakları ile sürdürülebilir gıda üretimini güvence altına alma kapasitelerini giderek daha fazla tehdit etmektedir. Bu bağlantılı sorunlar, tarımsal faaliyetlerin sınırlı ve belirsiz su kaynaklarına bağımlı olduğu kurak ve yarı kurak bölgelerde daha belirgin hâle gelmektedir. Bu çalışma, seçilmiş öncü uluslararası deneyimlerin analitik olarak incelenmesi yoluyla modern teknolojilerin su ve gıda güvenliğini güçlendirmedeki rolünü araştırmaktadır. Çalışmada öncelikle modern teknoloji, su güvenliği ve gıda güvenliği kavramları açıklanmış; ardından su kaynaklarının rasyonel ve sürdürülebilir yönetimini ve tarımsal gelişmeyi destekleyen teknolojik uygulamalar değerlendirilmiştir. Araştırmada kavramsal literatüre, dokümanlara ve uluslararası uygulamaların karşılaştırmalı incelemesine dayanan betimsel-analitik bir yaklaşım benimsenmiştir. İnceleme; hava modifikasyonu ve kuraklık yönetimi teknolojilerini, atık suyun arıtılması ve yeniden kullanımını, deniz suyunun tuzdan arındırılmasını, buharlaşmanın kontrolünü, su tasarruflu sulama sistemlerini ve su varlığını artırmayı veya kayıpları azaltmayı amaçlayan diğer yenilikleri kapsamaktadır. Bulgular, modern teknolojilerin su arzını çeşitlendirerek, kaynak kullanım verimliliğini artırarak, geleneksel olmayan su kaynaklarının yeniden kullanılmasını sağlayarak ve tarımsal dayanıklılığı güçlendirerek su sürdürülebilirliğine önemli katkılar sunabileceğini göstermektedir. Bu teknolojilerin gıda güvenliğine katkısı ise daha güvenilir sulama, yükselen su verimliliği, kuraklığa karşı azalan kırılganlık ve tarımsal üretimin devamlılığı aracılığıyla gerçekleşmektedir. Bununla birlikte sürdürülebilir sonuçlar yalnızca teknolojiyle sağlanamaz. Başarı; kurumsal kapasiteye, uygun düzenlemelere, finansmana, teknik uzmanlığa, bakıma, çevresel değerlendirmeye ve teknolojilerin yerel koşullara uyarlanmasına bağlıdır. Özellikle Kuzey Afrika'daki gelişmekte olan ülkelerin uygun teknolojileri bütünleşik su ve tarım politikalarına dâhil etmeleri önerilmektedir.

Anahtar Kelimeler: modern teknoloji; su güvenliği; gıda güvenliği; atık suyun yeniden kullanımı; deniz suyunun tuzdan arındırılması; sürdürülebilir tarım

1. Introduction

Water security and food security have become closely interconnected development priorities in an era characterized by climate change, population growth, urbanization, ecosystem degradation, and intensifying competition for natural resources. Water supports domestic consumption, sanitation, energy generation, industry, ecosystem functioning, and agricultural production. Its availability, quality, accessibility, and sustainable management consequently influence economic stability, public health, social well-being, and national security. Food security is similarly multidimensional, requiring the continuing availability, accessibility, utilization, and stability of sufficient and nutritious food.

The relationship between the two concepts is particularly strong because agriculture is the largest user of freshwater globally. Approximately 70–72% of global freshwater withdrawals are allocated to agriculture, making agricultural production highly vulnerable to water scarcity, drought, declining groundwater reserves, and changes in rainfall patterns (UNESCO World Water Assessment Programme, 2024). Water insecurity can reduce cultivated areas, lower crop yields, increase production costs, destabilize rural livelihoods, and increase dependence on food imports. Conversely, inefficient agricultural water use may intensify water stress and reduce the availability of resources for households, ecosystems, and other economic sectors.

These pressures are especially severe in arid and semi-arid regions, including North Africa, where low and variable precipitation, recurrent drought, high evaporation rates, and limited renewable freshwater resources constrain agricultural development. Climate change adds further uncertainty by modifying precipitation patterns and increasing the frequency or severity of certain extreme events. The Intergovernmental Panel on Climate Change concludes that climate-related changes and intensifying extremes have already adversely affected food security and terrestrial ecosystems (IPCC, 2019). Water and food policies can therefore no longer be developed independently of climate adaptation and resilience planning.

Recent global evidence illustrates the scale of the challenge. Roughly half of the global population experiences severe water scarcity during at least part of the year, while droughts affected more than 1.4 billion people between 2002 and 2021. The same evidence indicates that none of the Sustainable Development Goal 6 targets appears to be on track (UNESCO World Water Assessment Programme, 2024). Water insecurity is consequently not only an environmental problem but also a constraint on poverty reduction, agricultural productivity, public health, migration management, and social stability.

Traditional supply expansion and conventional agricultural practices are increasingly insufficient to address these interconnected pressures. Countries are therefore adopting technological interventions intended to diversify water sources, improve water-use efficiency, reduce losses, strengthen monitoring, and increase the resilience of food production. Such interventions include wastewater treatment and reuse, desalination, precision irrigation, smart water networks, remote sensing, water harvesting, drought-monitoring systems, evaporation-reduction techniques, protected agriculture, climate-resilient crops, and selected forms of weather modification.

Modern technology should not be understood merely as the acquisition of machines or equipment. It encompasses scientific knowledge, technical processes, information systems, infrastructure, institutional capabilities, and problem-solving practices used to improve human and organizational performance. Farajallah and Ben Soueilh (2021) similarly conceptualize technology as an applied system connecting information, skills, experience, and material resources. This broader interpretation is important because the success of water and agricultural technologies depends on the institutions, competencies, maintenance systems, regulatory frameworks, and knowledge networks within which they operate.

Wastewater treatment and reuse represent one important technological pathway. Appropriately treated wastewater can supplement conventional supplies, particularly for agriculture, landscaping, industry, and groundwater recharge. Its use can reduce pressure on freshwater resources while recovering water that might otherwise be discharged untreated. However, reuse requires reliable treatment standards, monitoring, infrastructure, public acceptance, and safeguards for human and environmental health. Lower-income countries frequently experience water-quality problems partly because of inadequate wastewater treatment, demonstrating that technological availability must be supported by institutional and financial capacity (UNESCO World Water Assessment Programme, 2024).

Desalination provides another mechanism for increasing water supply in water-scarce coastal regions. Advances in membrane systems, energy recovery, renewable energy integration, and operational efficiency have expanded its strategic relevance. Nevertheless, desalination can involve high financial and energy costs and may generate environmental concerns associated with brine disposal. It should therefore be incorporated into diversified water portfolios based on economic feasibility, environmental assessment, and long-term sustainability rather than treated as a universal solution.

Technology can also reduce agricultural demand for water. Precision irrigation, soil-moisture sensors, satellite data, automated control systems, and crop-monitoring platforms enable farmers and water managers to align irrigation more closely with crop requirements. Such approaches may reduce over-irrigation, improve water productivity, and provide earlier warnings of crop stress. Their effectiveness, however, depends on affordability, connectivity, technical support, farmer training, and compatibility with farm size and local production systems.

The significance of reliable irrigation extends beyond direct increases in production. In semi-arid regions, irrigation can stabilize yields, reduce the probability of crop failure, protect rural livelihoods, and improve the continuity of food supplies. UNESCO emphasizes that investment in agriculture is critical where population growth, climate change, and competition for water resources interact; agricultural production is particularly exposed to climate-related water risks (UNESCO World Water Assessment Programme, 2024).

Weather-related technologies and drought-management systems constitute a further area of interest. Forecasting, early-warning systems, satellite monitoring, and climate-information services can improve preparedness and support decisions concerning planting, irrigation, reservoir management, and emergency response. Certain countries have also experimented with weather-modification technologies. Their effectiveness and environmental implications, however, should be assessed carefully through transparent scientific evaluation. Technological optimism must not replace evidence-based risk analysis.

The international experience demonstrates that no single technology can resolve the water–food security challenge. Successful approaches generally combine infrastructure with governance, financing, regulation, scientific research, institutional cooperation, and local participation. The 2023 United Nations World Water Development Report emphasizes that sustainable water management and the protection of water, food, and energy security require collaboration across sectors and stakeholders (UNESCO World Water Assessment Programme, 2023). Technology transfer should therefore involve not only equipment but also knowledge, maintenance capacity, regulatory experience, and long-term institutional partnerships.

Developing countries face particular barriers to technological adoption, including restricted financing, dependence on imported equipment, limited research and development capacity, inadequate infrastructure, shortages of specialized personnel, and fragmented governance. Technologies successful in high-income countries may not produce equivalent outcomes when transferred without adaptation. Differences in energy costs, water quality, climate, farm structure, regulatory capacity, and community acceptance must be considered. The appropriate question is therefore not whether technology should be adopted in general, but which technologies are suitable, under what conditions, for which users, and with what environmental and distributive consequences.

Against this background, the present study investigates whether and how modern technology can strengthen water and food security. It addresses three questions: What is meant by modern technology, water security, and food security? Through which mechanisms can technology support water sustainability and agricultural production? What lessons can developing countries derive from leading international experiences?

The study employs descriptive and analytical methods. Its conceptual component clarifies the central terms and their interrelationships, while its applied component evaluates selected international practices involving water-supply diversification, efficiency improvement, wastewater reuse, desalination, drought management, and loss reduction. The central proposition is that modern technology constitutes an important mechanism through which advanced countries pursue rational and sustainable water management and, indirectly, strengthen food security.

This study contributes by integrating water security and food security within a unified technological framework. It argues that technological adoption should form part of comprehensive policy rather than consist of isolated projects. For North African countries in particular, strengthening water and food security requires a balanced portfolio combining appropriate technology, institutional reform, professional capacity, environmental safeguards, regional cooperation, research investment, and locally adapted implementation.

Literature Review

Water Security as a Multidimensional Development Concept

Water security has evolved from a narrow focus on the physical availability of water to a multidimensional concept encompassing availability, accessibility, quality, affordability, sustainability, risk management, and institutional governance. It concerns whether individuals, communities, economic sectors, and ecosystems have reliable access to water of sufficient quantity and acceptable quality while remaining protected from drought, floods, pollution, resource depletion, and other water-related risks.

Boussaq and Majdan (2022) examine the conceptual development and growing importance of water security. Their approach indicates that water security should not be reduced to the amount of water physically available within a country. It must also include the effectiveness of water management, the capacity to respond to scarcity, the protection of water quality, and the sustainability of supply across generations. This broader interpretation is particularly relevant to arid and semi-arid countries, where climatic variability and limited renewable resources increase the importance of governance and technological adaptation.

In Algeria, the water-security question is closely related to regional disparities, recurrent drought, population concentration, agricultural demand, infrastructure capacity, and the sustainable management of surface and groundwater. Takouasht (2024) explicitly connects water-security policies with the achievement of food security. This relationship is significant because agriculture depends on the availability and reliability of water, while inefficient irrigation and uncontrolled extraction may intensify scarcity. Water policy therefore constitutes an integral part of agricultural and food-security strategy.

Mazouni (2024) extends the discussion by examining how water security is represented in Algerian public television. This perspective draws attention to the communicative and social dimensions of resource security. Public understanding, media framing, and awareness campaigns can influence water-consumption behavior, support acceptance of conservation policies, and strengthen societal engagement with long-term resource challenges. Water security consequently requires not only technical and governmental interventions but also informed public participation.

Food Security and the Algerian Context

Food security is generally associated with the continuing availability, accessibility, utilization, and stability of adequate and nutritious food. National self-sufficiency can contribute to food security, but the two concepts should not be treated as identical. A country may rely partly on imports while maintaining food security if it possesses stable supply chains, sufficient foreign-exchange capacity, and effective social-protection mechanisms. Conversely, high domestic production does not automatically guarantee household access or nutritional adequacy.

Nasser (2010) examines policies for achieving food security in developing countries through the case of Algeria. This contribution situates food security within the wider economic and policy environment, where domestic production, import dependence, agricultural investment, market regulation, and state support interact. For developing countries, food security is affected by structural constraints that may include limited productivity, dependence on rainfall, price volatility, inadequate storage, logistical weaknesses, and exposure to international-market disruptions.

Ben Nourine and Bou Abdellah (2021) focus on sustainable food security and the mechanisms through which it can be achieved in Algeria. The emphasis on sustainability is important because short-term increases in production may undermine long-term security if they depend on groundwater depletion, soil degradation, inefficient irrigation, or environmentally harmful practices. Sustainable food security requires agricultural production to be increased or stabilized without compromising the natural-resource base on which future production depends.

Ashouri (2024) examines Algeria's food-security challenges in a more recent context. The study's thematic focus suggests that food security remains a multidimensional national concern involving production capacity, import dependence, environmental constraints, water availability, institutional coordination, and external economic pressures. Together, these studies indicate that Algeria requires an integrated food-security strategy combining agricultural development, water management, technology, market stability, infrastructure, and social policy.

The Water–Food Security Nexus

The reviewed literature demonstrates that water security and food security are structurally interconnected. Water is an essential input in crop production, livestock farming, food processing, and rural livelihoods. Variability in water availability can affect cultivated areas, productivity, production costs, food prices, and import requirements. Agricultural expansion may simultaneously increase pressure on already limited water resources.

Takouasht (2024) provides the clearest policy-oriented treatment of this relationship by presenting water-security policy as a strategy for achieving food security. The implication is that agricultural policy cannot be successful when developed separately from water policy. Decisions concerning crop selection, irrigation expansion, groundwater extraction, wastewater reuse, desalination, and agricultural investment must be coordinated within a common planning framework.

This relationship also introduces trade-offs. Expanding irrigation may stabilize agricultural production but can intensify resource depletion if water abstraction exceeds renewable supply. Increasing domestic production may improve national food availability while reducing water availability for households, industry, or ecosystems. An effective policy must therefore consider water productivity—the value or agricultural output generated per unit of water—rather than focusing only on total agricultural production.

The literature consequently supports a nexus-based approach in which water, agriculture, food, energy, environment, and economic policy are analyzed as interdependent systems. Modern technology can play an important role within this framework, but it must be selected and evaluated according to its contribution to the sustainability of the entire system.

Modern Technology and Water-Resource Security

Modern technology offers several mechanisms for strengthening water security. These include seawater desalination, wastewater treatment and reuse, precision irrigation, smart metering, remote sensing, geographic information systems, leak detection, water-quality monitoring, drought forecasting, water harvesting, and evaporation-control techniques. Such technologies may increase supply, reduce losses, improve allocation, or strengthen the information available to decision-makers.

Ben Ghida and Harakat (2020) specifically examine the use of modern technologies to achieve water-resource security through selected global experiences. Their focus is particularly relevant to the present study because international cases can demonstrate how countries facing scarcity have diversified water supplies, increased reuse, improved irrigation efficiency, and introduced monitoring systems. Comparative experience can experience can offer practical lessons, but technological models should not be transferred mechanically. Their success depends on economic capacity, climate, energy availability, technical expertise, regulatory systems, and institutional effectiveness.

Technology can contribute to water security through both supply-side and demand-side mechanisms. Supply-side technologies include desalination, wastewater reuse, artificial recharge, and selected weather-modification interventions. Demand-side technologies include efficient irrigation, smart monitoring, leakage control, and digital allocation systems. A balanced strategy should avoid excessive dependence on supply expansion and simultaneously improve efficiency, conservation, and governance.

The reviewed literature also implies that technological interventions require environmental evaluation. Desalination may increase water availability but can involve high energy use and brine-management challenges. Wastewater reuse may support agriculture but requires reliable treatment and health safeguards. Precision irrigation may reduce water application at the field level, although its broader effects depend on crop choices and total irrigated area. Technology should therefore be assessed according to life-cycle costs, environmental risks, distributional consequences, and long-term maintenance requirements.

Agricultural Technology and Food Security

Qattaf (2025) examines agricultural technology as a response to the global food crisis through international experiences. Agricultural technology may strengthen food security by increasing productivity, reducing water and input use, improving climate resilience, limiting post-harvest losses, and supporting more accurate decision-making. Relevant applications include precision agriculture, protected cultivation, drought-resistant crop varieties, soil-moisture monitoring, automated irrigation, satellite-based crop observation, and digital advisory services.

The value of agricultural technology is especially important where water scarcity restricts conventional production. Precision irrigation and soil monitoring can help align water application with crop requirements. Protected agriculture may reduce exposure to extreme weather and improve control over water and nutrients. Remote sensing can support early detection of drought, crop stress, or disease. Digital information platforms can provide farmers with weather, market, and technical information.

Nevertheless, agricultural technology is not socially or institutionally neutral. Its adoption may be limited by financial costs, farm size, access to credit, connectivity, technical literacy, and the availability of maintenance services. Large commercial farms may benefit more quickly than smallholders unless public policy includes inclusive financing, training, extension services, and shared infrastructure. The contribution of technology to food security should therefore be evaluated not only through productivity but also through accessibility, affordability, and distributional equity.

Technology Transfer and Human Capacity

Tetteh et al. (2022) examine the concept of technology and the role of commercial companies in its transfer. Technology transfer is significant for developing countries that depend on imported machinery, software, patents, and technical expertise. However, genuine transfer involves more than purchasing equipment. It requires the acquisition of knowledge, operational competence, maintenance capacity, adaptation skills, and, where possible, domestic research and manufacturing capabilities.

Commercial companies can facilitate access to advanced technologies, but reliance on external suppliers may create financial and strategic dependencies. Imported systems may be difficult to maintain when spare parts, software support, or specialized expertise are unavailable locally. Technology-transfer agreements should therefore include training, maintenance arrangements, knowledge sharing, and opportunities for local adaptation.

Farajallah and Ben Soueilh (2021) emphasize the relationship between modern technology and the quality performance of human resources. This perspective is crucial because technological systems achieve their intended outcomes only when personnel possess the capacity to operate, manage, evaluate, and improve them. Investment in human capital should accompany investment in infrastructure. Universities, research centers, agricultural-extension institutions, water agencies, and technical-training organizations all have roles in building the necessary competencies.

Synthesis and Research Gap

The reviewed scholarship addresses several important dimensions of the research problem. Studies of water security clarify its conceptual development and policy relevance (Boussaq & Majdan, 2022; Mazouni, 2024). Research on food security identifies sustainability challenges and policy requirements in Algeria (Ashouri, 2024; Ben Nourine & Bou Abdellah, 2021; Nasser, 2010). Other studies examine the water–food nexus, technological solutions, international experiences, agricultural innovation, technology transfer, and human-resource development (Ben Ghida & Harakat, 2020; Farajallah & Ben Soueilh, 2021; Qattaf, 2025; Takouasht, 2024; Tetteh et al., 2022).

However, these dimensions are frequently examined separately. Some studies concentrate on conceptual or policy questions, while others focus on specific technologies or one dimension of security. Comparatively less attention is given to an integrated analytical framework connecting modern technology, sustainable water management, agricultural resilience, food security, technology transfer, and institutional capacity.

The present study addresses this gap by examining modern technology as a common mechanism linking water and food security. It draws on leading international experiences to identify technological applications, enabling conditions, limitations, and lessons relevant to developing countries, particularly those in North Africa. Its contribution lies not in presenting technology as an automatic solution but in demonstrating that its effectiveness depends on integrated governance, human capacity, financing, environmental safeguards, local adaptation, and long-term institutional commitment.

3. Methodology

3.1. Research Design

This study adopted a qualitative, descriptive–analytical, and comparative research design to examine how modern technologies may contribute to strengthening water and food security. The research combined an integrative review of the relevant literature with qualitative document analysis and a structured comparison of selected international experiences.

This design was appropriate because the study sought to explain concepts, identify technological mechanisms, compare policy experiences, and derive lessons for developing countries rather than measure individual attitudes or estimate causal effects statistically. Integrative reviews are suitable for synthesizing conceptually and methodologically diverse sources, while document analysis provides a systematic procedure for interpreting published materials in relation to predefined research questions (Bowen, 2009; Snyder, 2019).

The study consisted of two interconnected components. The first developed the conceptual framework by examining modern technology, water security, food security, and the relationship between water availability and agricultural production. The second analyzed selected international applications of technologies used to increase water availability, improve water-use efficiency, reduce losses, manage drought, and support agricultural resilience.

3.2. Research Questions

The methodological procedure was guided by the following principal research question:

How can modern technologies contribute to strengthening water and food security, and what lessons can developing countries draw from leading international experiences?

Three subsidiary questions structured the analysis:

1. How are modern technology, water security, and food security conceptualized in the relevant literature?
2. Through which technological mechanisms can water availability, efficiency, sustainability, and agricultural productivity be improved?
3. Which institutional, economic, technical, environmental, and regulatory conditions influence the transferability of international experiences to developing countries, particularly those in North Africa?

These questions determined the selection of documents, technological categories, and comparative criteria.

3.3. Analytical Scope and Units of Analysis

The study treated the technological intervention or international experience as the principal unit of analysis. Each case was examined as a combination of:

- a water- or food-security problem;
- a technological response;
- an institutional and geographical context;
- an implementation mechanism;
- reported outcomes;
- limitations or risks;
- and potential lessons for developing countries.

The analysis covered technologies that influence either the supply of water or the efficiency with which water is used. Supply-side interventions included wastewater treatment and reuse, seawater desalination, evaporation control, water harvesting, and selected weather-modification practices. Demand-side and agricultural interventions included efficient irrigation, agricultural monitoring, drought forecasting, precision water management, and technologies intended to improve crop resilience or agricultural water productivity.

Modern technology was therefore conceptualized broadly as the interaction of scientific knowledge, technical equipment, information systems, infrastructure, professional competence, and institutional arrangements. This avoided reducing technology to physical devices alone.

3.4. Documentary Sources

The documentary corpus comprised peer-reviewed journal articles, academic books, legal and policy documents, institutional publications, conference papers, and reports addressing water security, food security, agricultural technology, wastewater reuse, desalination, drought management, weather modification, and technology transfer.

The reviewed Algerian literature included studies on national food-security challenges, sustainable food security, water-security policies, public communication, technological applications, and technology transfer (Ashouri, 2024; Ben Ghida & Harakat, 2020; Ben Nourine & Bou Abdellah, 2021; Boussaq & Majdan, 2022; Mazouni, 2024; Nasser, 2010; Qattaf, 2025; Takouasht, 2024; Tetteh et al., 2022). International institutional reports were used to situate the selected cases within broader discussions of climate risk, water stress, agricultural demand, and sustainable resource management.

Source types were weighted according to their evidentiary role. Peer-reviewed research and authoritative institutional reports were prioritized when assessing technological performance and environmental implications. National laws and policy documents were used to clarify regulatory definitions and institutional objectives. Conference papers and media-related materials were used primarily to identify emerging practices, public narratives, or potential cases requiring further verification.

3.5. Source and Case Selection Criteria

Documents were included when they met at least one of the following criteria:

1. They provided a definition or analytical treatment of water security, food security, or modern technology.

2. They examined a technological intervention directly related to water availability, water quality, water-use efficiency, agricultural productivity, or climate resilience.
3. They presented an identifiable national or regional experience involving the application of modern technology to water or agricultural management.
4. They described implementation requirements, outcomes, risks, financing needs, governance mechanisms, or technology-transfer processes.
5. They offered findings with potential relevance to water-scarce developing countries.

Documents were excluded from the central analysis when they discussed technology without a meaningful connection to water or food security, made unsupported promotional claims, or provided insufficient information to identify the technology, context, and intended outcome.

International experiences were selected purposively rather than statistically. Purposive case selection is appropriate when cases are chosen for their analytical relevance, technological distinctiveness, or capacity to illuminate a defined research problem (Yin, 2018). The cases were intended to represent different technological pathways rather than all global water- and food-security initiatives.

3.6. Comparative Analytical Framework

A structured, focused comparison was employed to improve consistency across the international experiences. In structured comparison, each case is examined through the same set of questions, allowing similarities, differences, and transferable lessons to be identified systematically (George & Bennett, 2005).

Each case was analyzed according to the following dimensions:

Analytical dimension	Guiding question
Security challenge	What water- or food-security problem was the technology intended to address?
Technological intervention	What technology or technical system was introduced?
Functional mechanism	Did it increase supply, reduce loss, improve quality, strengthen monitoring, or increase agricultural productivity?
Implementation context	Under what climatic, economic, institutional, and geographic conditions was it applied?
Enabling conditions	Which infrastructure, skills, regulations, financing, and partnerships supported implementation?
Reported outcomes	What benefits or performance improvements were reported?
Risks and limitations	What financial, environmental, technical, ethical, or governance concerns were identified?
Transferability	Under what conditions could the experience be adapted to North African or other developing-country contexts?

The framework prevented the analysis from treating technological success as an isolated technical outcome. It required attention to the institutional and environmental conditions influencing implementation.

3.7. Data-Extraction Procedure

Relevant information was extracted from each document using a standardized analytical matrix. The matrix recorded:

- bibliographic information;
- country or regional setting;
- water- or food-security challenge;
- type of technology;
- intended beneficiaries;
- scale of implementation;
- reported environmental and economic outcomes;
- implementation requirements;
- constraints and uncertainties;
- and policy relevance.

When different documents described the same technology or case, the accounts were compared for consistency. Numerical or performance claims were retained only when their source and context could be identified. Claims relating to technically contested interventions—particularly weather modification—were interpreted cautiously and distinguished from independently verified effects.

No statistical meta-analysis was performed because the reviewed studies differed substantially in research design, units of measurement, geographical context, technology type, and outcome reporting. The synthesis was consequently qualitative and explanatory rather than based on pooled effect sizes.

3.8. Analytical Procedure

The analysis was conducted in five stages.

Stage 1: Conceptual clarification. Definitions of modern technology, water security, food security, sustainability, and technology transfer were collected and compared. Particular attention was given to the difference between national food self-sufficiency and the broader concept of food security.

Stage 2: Technological classification.
The identified technologies were classified according to their principal function:

- increasing or diversifying water supply;
- improving water quality;
- reducing evaporation or distribution losses;
- increasing agricultural water-use efficiency;
- monitoring climatic and hydrological conditions;
- strengthening drought preparedness;
- or improving agricultural productivity and resilience.

Stage 3: Within-case analysis.
Each international experience was examined individually to determine its objectives, implementation context, reported outcomes, constraints, and underlying institutional conditions.

Stage 4: Cross-case comparison.
The cases were compared using the common analytical framework. Recurrent patterns were identified across technological effectiveness, infrastructure, financing, governance, technical competence, environmental impact, and long-term maintenance.

Stage 5: Interpretive synthesis.
The recurring findings were integrated into a set of policy lessons for developing countries. The synthesis distinguished between technologies that might be directly adaptable, those requiring substantial institutional preparation, and those whose effectiveness remained context-dependent or scientifically uncertain.

Qualitative coding and thematic categorization followed the principles of data condensation, pattern identification, comparison, and interpretive verification described by Miles et al. (2020).

3.9. Evaluation of Technological Contribution

The contribution of technology to water security was evaluated through four principal dimensions:

1. **Availability:** the extent to which the intervention increased, diversified, recovered, or protected usable water supplies;
2. **Efficiency:** the extent to which it reduced water consumption, leakage, evaporation, or unnecessary application;
3. **Quality and safety:** the extent to which it improved water quality while controlling health and environmental risks;
4. **Resilience:** the extent to which it strengthened capacity to manage drought, climate variability, supply disruption, or rising demand.

Its contribution to food security was evaluated according to:

- agricultural-water reliability;
- productivity and water productivity;
- stability of production under climatic stress;
- reduction of crop-loss risk;
- support for rural livelihoods;
- and the accessibility and affordability of the intervention.

Because the source materials did not employ common quantitative indicators, the study did not assign composite scores or rankings to countries. Instead, it assessed the direction, mechanism, and contextual credibility of the reported contribution.

3.10. Trustworthiness and Source Criticism

Several procedures were used to strengthen the credibility of the study. First, evidence was compared across different source types rather than relying on a single account. Second, conceptual, legal, technical, and policy materials were used for distinct analytical purposes. Third, the study distinguished reported outcomes from independently verified results and from the authors' interpretations.

Fourth, technological benefits were examined together with costs, environmental risks, operational requirements, and governance limitations. Fifth, conflicting evidence was not removed solely to produce a uniform conclusion. Documentary analysis requires sources to be assessed in relation to their purpose, authorship, context, intended audience, and evidentiary limitations (Bowen, 2009).

An analytical audit trail was maintained through the use of common extraction categories and case-comparison questions. This strengthened consistency and made the reasoning connecting the documentary evidence to the conclusions more transparent.

3.11. Ethical Considerations

The study relied exclusively on publicly available academic, legal, policy, and institutional documents. It did not involve human participants, interviews, surveys, experiments, personal data, or confidential records. Formal approval from a research ethics committee was therefore not required.

Nevertheless, principles of research integrity were observed by citing all sources, representing claims accurately, avoiding the fabrication of missing data, and distinguishing evidence-based conclusions from recommendations or interpretations.

3.12. Methodological Limitations

The study has several limitations. First, the international cases were selected purposively and do not represent every technological experience worldwide. Second, the reviewed documents differed in methodological quality, geographical scale, outcome measurement, and publication purpose. Third, some technologies were supported by stronger evidence than others. Claims concerning weather modification, in particular, may be affected by uncertainty regarding attribution, measurement, and environmental consequences.

Fourth, the absence of comparable cost, energy, environmental-impact, and performance data prevented statistical comparison or formal ranking. Fifth, practices successful in advanced economies may not be directly transferable to North Africa because of differences in financing, governance, infrastructure, technical capacity, energy systems, and climatic conditions.

Accordingly, the conclusions should be interpreted as a structured qualitative synthesis and source of policy-relevant lessons rather than as proof that a particular technology will produce equivalent effects in every national setting.

4. Results

4.1. Overview of the Documentary Synthesis

The comparative analysis identified nine international experiences representing five principal technological pathways: atmospheric water enhancement and drought management; wastewater treatment and reuse; biological improvement of plant water-use efficiency; reduction of water losses; and technology-intensive agricultural production. The cases covered China, the United States, Belgium, India, Japan, Saudi Arabia, and the United Arab Emirates.

The evidence indicates that modern technology can contribute to water and food security through three general mechanisms. First, supply-oriented technologies can diversify usable water sources through wastewater treatment, reuse, and desalination. Second, efficiency-oriented technologies can reduce evaporation, consumption, leakage, or unnecessary irrigation. Third, production-oriented technologies can improve crop resilience, agricultural water productivity, monitoring, and continuity of food production under difficult climatic conditions.

However, the documentary evidence was not equally strong across all cases. Some interventions, including wastewater treatment, precision irrigation, protected cultivation, and desalination, are supported by established scientific and operational principles. Other interventions—particularly large-scale weather modification and some reported performance percentages—require cautious interpretation because the reviewed secondary sources did not always provide sufficiently detailed methodological verification.

4.2. Weather Modification and Drought Management

The first experience concerned the use of weather-modification technologies in China and selected locations in the United States. The reviewed documents described cloud seeding as an intervention intended to increase precipitation, reduce hail, or mitigate certain effects of drought. The Chinese experience was presented as an example of substantial institutional investment in weather-management programs, while the United States examples included aircraft- and drone-assisted delivery systems (Ben Ghida & Harakat, 2020).

These cases demonstrate the potential role of technological innovation in strengthening drought preparedness and atmospheric monitoring. Nevertheless, the effectiveness of cloud seeding is strongly dependent on pre-existing meteorological conditions. It cannot create moisture where suitable clouds are absent, and observed changes in rainfall are difficult to attribute exclusively to intervention because precipitation is naturally variable. Consequently, weather modification should be treated as a supplementary and context-dependent measure rather than a reliable substitute for conservation, storage, reuse, irrigation efficiency, or drought planning.

The principal result from this case is therefore not that weather modification guarantees additional water, but that some countries have developed technical and institutional capacities to experiment with atmospheric interventions. The transferability of these programs to developing countries would require meteorological infrastructure, scientific expertise, transparent evaluation, environmental regulation, and sustained financing.

4.3. Wastewater Treatment and Reuse

The second technological pathway involved wastewater treatment and reuse. The Belgian example described a solar-powered system designed to produce purified water and fertilizer, indicating the potential of decentralized treatment in rural or off-grid areas. The Indian cases involved biological treatment processes using algae, plants, microorganisms, and natural materials to remove nutrients or selected contaminants from wastewater (Ben Ghida & Harakat, 2020).

The analysis indicates that wastewater reuse can contribute to water security by recovering a resource that would otherwise remain polluted or be discharged unused. Its application in agriculture can reduce pressure on freshwater sources, provide more stable irrigation supplies, and potentially recover nutrients. Decentralized systems may be particularly relevant to rural communities where conventional treatment infrastructure is unavailable or financially impractical.

Biological treatment technologies may offer lower-energy alternatives to some conventional processes. However, their performance depends on contaminant type, treatment duration, system design, environmental conditions, and operational control. Removal of selected metals or nutrients does not necessarily mean that treated water is safe for drinking or unrestricted agricultural use. Pathogens, chemical residues, salinity, and emerging contaminants must also be considered.

The reviewed documents themselves acknowledged the health and environmental risks arising from insufficient treatment. Accordingly, wastewater reuse requires defined water-quality standards, continuous monitoring, treatment appropriate to the intended use, and clear institutional responsibility. This result supports a “fit-for-purpose” approach: the required treatment level should correspond to whether the water will be used for industrial activity, restricted irrigation, food-crop irrigation, groundwater recharge, or human consumption.

4.4. Biological Technologies for Agricultural Water Efficiency

The third experience examined the use of mycorrhizal fungi and other beneficial microorganisms to support plant growth under water scarcity. These organisms can form associations with plant roots and potentially enhance access to water and nutrients. The reviewed Indian experience associated microbial fertilizers with improved water absorption, reduced irrigation requirements, better soil-water retention, and increased crop resilience (Ben Ghida & Harakat, 2020).

This case illustrates how water security can be strengthened not only by increasing supply but also by improving biological efficiency. Technologies that enable plants to use available water more effectively may reduce vulnerability to drought and improve agricultural productivity. They may also complement other practices, including precision irrigation, soil management, crop diversification, and the use of locally appropriate varieties.

However, biological responses depend on crop species, soil conditions, microbial strain, temperature, salinity, farming practices, and ecological compatibility. Successful experimental outcomes cannot automatically be generalized across regions. Large-scale adoption requires local field trials, quality control of microbial products, farmer training, and assessment of long-term ecological effects.

A related case involved OPABACTIN, a synthetic compound developed to imitate the drought-response function of abscisic acid. The reviewed material presented this intervention as a possible mechanism for helping plants reduce water loss during drought. This technology remains more experimental than established water-treatment or irrigation systems. Its agricultural value should therefore be assessed through replicated field research addressing effectiveness, cost, crop response, environmental safety, and accessibility to farmers.

4.5. Technologies for Reducing Water Loss and Consumption

The United States shade-ball case and Japan's Bubble 90 nozzle represented two different approaches to water conservation. Shade balls were deployed on a drinking-water reservoir in Los Angeles to reduce sunlight exposure, suppress certain chemical reactions, limit contamination, and reduce evaporation. The original documentary source reported substantial expected water savings, although the present study could not independently verify the calculation or evaluate the complete life-cycle balance of producing, maintaining, and eventually disposing of the plastic balls (Ben Ghida & Harakat, 2020).

The Japanese Bubble 90 nozzle was presented as a demand-side technology designed to reduce water use during washing by generating a pulsating air–water flow without electricity. The case demonstrates how relatively small technological modifications can potentially generate cumulative savings when implemented across a large number of users.

These cases show that water-security technology does not always require large dams, treatment plants, or national infrastructure. Targeted interventions at reservoirs, buildings, farms, businesses, and households may contribute to demand management. Nevertheless, reported water savings should be evaluated in relation to baseline consumption, actual user behavior, maintenance requirements, rebound effects, product durability, and total environmental cost.

4.6. Desalination and Non-Conventional Water Supply

The Saudi Arabian experience demonstrated the strategic role of desalination in countries with limited renewable freshwater resources. The reviewed documents discussed the historical development of desalination and a newer electrochemical approach intended to separate salts through a low-voltage process (Ben Ghida & Harakat, 2020).

Desalination can strengthen water security by converting seawater or brackish water into a usable supply independent of rainfall. It is particularly relevant to water-scarce coastal countries. However, conventional desalination may require substantial capital, energy, specialized maintenance, and environmental management. Brine disposal, marine impacts, energy dependence, and the affordability of delivered water remain important concerns.

Electrochemical and nanoscale technologies may reduce some limitations, but laboratory or startup-stage innovation should not be treated as equivalent to proven large-scale performance. Before adoption, such systems require independent technical validation, pilot testing, cost comparison, energy assessment, and environmental review.

The comparative result is that desalination should form part of a diversified water portfolio rather than function as a single national solution. Conservation, wastewater reuse, groundwater protection, efficient irrigation, and demand management remain necessary even where desalination capacity is substantial.

4.7. Agricultural Digitalization in India

The Indian experience combined precision agriculture, smart irrigation, soil-moisture sensing, drones, satellite information, digital farmer platforms, biotechnology, and improved crop varieties. The reviewed material associated these interventions with lower water consumption, improved productivity, better access to agricultural information, reduced market intermediation, and stronger drought preparedness (Qattaf, 2025).

The case indicates that agricultural technology can affect all four dimensions of food security. Productivity-enhancing technologies may improve food availability. Digital market platforms can improve economic access by connecting producers with buyers and potentially strengthening farm income. Climate information and early-warning systems can support stability by reducing exposure to weather-related shocks. Improved crop quality and management can contribute indirectly to utilization.

Nevertheless, the Indian experience also revealed inequalities in technological access between large and small producers. Digital systems may reproduce existing disparities where farmers lack affordable devices, connectivity, credit, technical literacy, or extension services. The result is that agricultural digitalization must be accompanied by inclusive financing, local-language services, training, rural connectivity, and safeguards for data ownership and farmer autonomy.

4.8. Controlled-Environment and Smart Agriculture in the United Arab Emirates

The United Arab Emirates experience involved protected cultivation, greenhouses, soilless farming, closed-environment agriculture, smart irrigation, and other systems designed to overcome heat, water scarcity, and poor soil conditions. These methods enable greater control over temperature, humidity, irrigation, nutrients, light, and other production variables. They can also support year-round production and more efficient use of land and water (Qattaf, 2025).

The UAE case illustrates how integrated technology, policy, financing, and private-sector participation can support agricultural production in an environmentally constrained setting. National programs and food-security strategies provide a framework for connecting innovation with investment, local production, environmental objectives, and supply-chain development.

However, controlled-environment agriculture may require substantial capital, energy, technical expertise, imported inputs, and continuous system management. Its sustainability depends on energy sources, crop selection, market value, and the efficiency of cooling and water-recycling systems. The model may be suitable for high-value crops but less economically appropriate for all staple foods. Transfer to lower-income countries therefore requires careful adaptation rather than direct replication.

4.9. Consolidated Results

Technological pathway	International experience	Principal contribution	Critical implementation condition
Weather modification	China and the United States	Potential supplementary rainfall enhancement and hail reduction	Suitable atmospheric conditions and independent scientific evaluation
Wastewater treatment and reuse	Belgium and India	Diversified supply, agricultural reuse, and possible nutrient recovery	Fit-for-purpose treatment, health standards, and continuous monitoring
Biological water-efficiency enhancement	India and California	Improved plant water uptake and drought response	Local field validation, quality control, affordability, and ecological assessment
Evaporation and consumption reduction	United States and Japan	Reduced reservoir losses or point-of-use consumption	Life-cycle evaluation, verified savings, maintenance, and user adoption
Desalination	Saudi Arabia	Rainfall-independent water supply	Energy efficiency, cost control, brine management, and technical capacity
Precision and digital agriculture	India	Improved irrigation, monitoring, market access, and resilience	Inclusive access, connectivity, farmer training, and data governance
Controlled-environment agriculture	United Arab Emirates	Year-round production and efficient resource management	Capital, energy, expertise, crop suitability, and recycling systems

5. Discussion

5.1. Technology as a Portfolio Rather Than a Single Solution

The results demonstrate that no individual technology can secure both water and food systems under all conditions. The reviewed experiences instead support a portfolio approach combining supply diversification, efficiency improvement, monitoring, biological innovation, agricultural modernization, and institutional reform.

This finding corresponds with Boussaq and Majdan's (2022) multidimensional understanding of water security. Water security cannot be reduced to physical supply because quality, access, sustainability, environmental protection, resilience, and governance are also essential. Similarly, food security involves more than production volume; it encompasses access, utilization, stability, and the capacity to withstand disruptions (Ashouri, 2024; Ben Nourine & Bou Abdellah, 2021).

A country may therefore expand desalination without improving agricultural efficiency, or introduce smart irrigation while allowing groundwater depletion to continue. Sustainable outcomes require technologies to be coordinated within integrated water, agriculture, energy, environmental, and economic policies.

5.2. The Centrality of the Water–Food Nexus

The comparative cases reinforce the structural relationship between water security and food security. Agriculture accounts for approximately 70–72% of freshwater withdrawals worldwide, while the proportion is higher in many water-scarce regions. Water scarcity consequently affects cultivated area, crop yields, production costs, rural income, food prices, and import dependence. Recent United Nations evidence likewise identifies agriculture as the dominant freshwater user and a sector particularly exposed to climate-related water risks (UNESCO World Water Assessment Programme, 2024).

Takouasht (2024) conceptualizes water-security policy as a strategy for achieving food security in Algeria. The international experiences support this proposition but add an important qualification: increasing water supply is only one component. Water productivity, reuse, crop selection, soil management, irrigation governance, and climate information may be equally important.

The policy objective should consequently shift from maximizing water withdrawal to maximizing sustainable social and agricultural value per unit of water. This requires evaluating which crops are produced, where they are produced, how water is allocated, and whether the resulting benefits justify financial and environmental costs.

5.3. Differences in Technological Maturity and Evidentiary Strength

An important finding is the uneven maturity of the reviewed technologies. Wastewater treatment, desalination, efficient irrigation, remote sensing, and protected cultivation have well-established technical foundations and widespread applications. Mycorrhizal technologies and drought-response compounds may be promising but require crop- and context-specific validation. Weather modification remains particularly difficult to evaluate because natural rainfall variability complicates causal attribution.

This distinction is essential for policy. Governments should not allocate resources solely on the basis of novelty, publicity, or reported success percentages. Technological adoption should be preceded by independent feasibility studies, pilot implementation, environmental assessment, and transparent comparison with available alternatives.

Ben Ghida and Harakat (2020) document a wide range of global technological experiences, but secondary descriptions of performance should be verified against primary technical evidence before they guide large-scale investment. The results of this study therefore support an evidence hierarchy in which peer-reviewed field research and independently monitored operational data receive greater weight than promotional or media-based claims.

5.4. Technology Transfer Requires Institutional Absorptive Capacity

The findings demonstrate that technology transfer involves more than importing machinery or purchasing patents. Tetteh et al. (2022) emphasize the role of commercial companies in transferring technology, while Farajallah and Ben Soueilh (2021) highlight the importance of human-resource performance. Together, these perspectives suggest that developing countries require absorptive capacity: the ability to understand, operate, maintain, adapt, evaluate, and improve imported technologies.

Without trained personnel, spare parts, laboratories, regulatory institutions, and long-term maintenance finance, advanced systems may remain underused or fail after initial implementation. Technology-transfer agreements should therefore incorporate training, local partnerships, maintenance responsibilities, knowledge sharing, and opportunities for domestic adaptation.

Universities and research institutions have a central role in this process. They can evaluate imported technologies, conduct local trials, train specialists, and develop solutions suited to national climatic and agricultural conditions. Regional research cooperation may be particularly useful for North African countries facing similar scarcity, drought, salinity, and desertification challenges.

5.5. Affordability, Equity, and the Risk of Technological Exclusion

The Indian experience indicates that technology can increase productivity while simultaneously creating or reinforcing disparities between producers. Large farms may adopt sensors, drones, controlled irrigation, and digital platforms more easily than smallholders. The same issue applies to desalination, biotechnology, and controlled-environment agriculture, which may require substantial capital and specialized knowledge.

Technology that improves aggregate production but excludes vulnerable farmers may not strengthen food security equitably. Food security concerns people's access to food, not only national production totals. Nasser (2010) and Ashouri (2024) situate Algerian food security within broader economic and social constraints, including purchasing power, import dependence, and production policy.

Public policy should therefore include concessional financing, cooperative ownership models, extension services, shared equipment, local-language platforms, rural connectivity, and targeted training. Distributional effects should form part of technology assessment alongside technical efficiency.

5.6. Environmental and Health Safeguards

Several cases present environmental trade-offs. Desalination can generate brine and require substantial energy. Wastewater reuse may create health risks where treatment and monitoring are inadequate. Plastic reservoir covers require life-cycle assessment. Biological products can interact with local ecosystems. Controlled-environment agriculture can consume significant energy.

Technology should consequently be evaluated through a water–energy–food–environment nexus. An intervention that saves water but sharply increases fossil-energy use or transfers pollution to another ecosystem may not represent a sustainable solution. Environmental-impact assessment, life-cycle costing, public-health standards, and post-implementation monitoring should therefore be mandatory components of adoption.

UNESCO's global water assessments similarly emphasize that water management must balance food production, livelihoods, ecosystems, energy, and social well-being rather than optimize a single objective (UNESCO World Water Assessment Programme, 2024).

5.7. Implications for Algeria and North Africa

The reviewed experiences offer several lessons for Algeria and other North African countries. First, wastewater treatment and reuse may provide a strategically important source for agriculture, landscaping, industry, and selected recharge applications. Expansion should be linked to quality standards, separate distribution infrastructure, and continuous monitoring.

Second, agricultural efficiency should be prioritized through soil-moisture monitoring, improved irrigation scheduling, precision systems, drought-resistant varieties, protected cultivation, and farmer advisory services. Technologies should be adapted to local crops, farm sizes, salinity conditions, and financial capacity.

Third, desalination may remain important for municipal and industrial supply, especially in coastal areas, but should be combined with renewable energy, brine-management strategies, and demand control. Using high-cost desalinated water for low-value crops may not always be economically sustainable.

Fourth, biological and chemical drought-resilience technologies should undergo local trials before large-scale adoption. Fifth, weather modification should not displace more reliable investments in storage, conservation, reuse, monitoring, and efficient irrigation.

Finally, Algeria requires a coordinated institutional framework connecting water authorities, agricultural agencies, universities, research laboratories, local government, farmers, private companies, and civil society. Public communication is also important because conservation and reuse policies depend partly on social acceptance and behavioral change (Mazouni, 2024).

5.8. Theoretical Contribution

This study contributes to the literature by developing an integrated interpretation of modern technology as a connecting mechanism between water security and food security. The findings suggest that technological contribution can be understood through four linked functions:

1. Resource augmentation: creating or recovering usable water;
2. Efficiency improvement: reducing water use and losses;
3. Resilience enhancement: improving capacity to withstand drought and climatic variability;
4. Production transformation: increasing the reliability and sustainability of agricultural output.

These functions operate within an enabling institutional environment comprising governance, finance, regulation, human capacity, scientific evidence, and social inclusion. Technology should therefore be conceptualized as a socio-technical system rather than an independent device.

The central conclusion of the discussion is that technology can make a substantial contribution to water and food security, but its results are conditional. Sustainable success depends on selecting appropriate technologies, verifying performance, adapting them locally, distributing benefits equitably, managing environmental risks, and maintaining long-term institutional capacity.

6. Conclusion

This study examined the role of modern technologies in strengthening water and food security through a descriptive–analytical review and structured comparison of selected international experiences. The cases covered weather modification and drought management, wastewater treatment and reuse, biological enhancement of plant water-use efficiency, evaporation and consumption reduction, desalination, precision agriculture, digital agricultural platforms, and controlled-environment production.

The comparative analysis demonstrates that modern technology can contribute to water security through four principal mechanisms: increasing or diversifying supply, improving water quality, reducing consumption and physical losses, and strengthening resilience to drought and climatic variability. Its contribution to food security is primarily achieved through more reliable irrigation, improved agricultural water productivity, reduced crop vulnerability, better monitoring, and greater continuity of agricultural production.

Wastewater treatment and reuse emerged as one of the most relevant options for water-scarce developing countries. Appropriately treated wastewater can supplement conventional supplies, reduce pressure on freshwater resources, and support agriculture. However, reuse cannot be considered safe or sustainable unless treatment standards correspond to the intended use and systems are supported by continuous monitoring, public-health safeguards, and clear institutional responsibility.

Desalination provides a rainfall-independent source of water and may be strategically important for coastal and highly water-scarce countries. Nevertheless, its long-term sustainability depends on energy efficiency, affordability, technical maintenance, brine management, and environmental protection. Emerging electrochemical and nanoscale desalination methods appear promising, but their suitability for large-scale implementation requires independent technical and economic validation.

The Indian and UAE experiences illustrate the potential contribution of precision irrigation, remote sensing, digital platforms, biotechnology, protected cultivation, hydroponics, vertical farming, artificial intelligence, and robotics. These technologies can improve resource efficiency and production stability, but their benefits may not be distributed equally. Farmers' access to finance, digital infrastructure, training, technical support, and markets substantially influences adoption.

The analysis also distinguishes between technologies according to their maturity and evidentiary strength. Wastewater treatment, desalination, efficient irrigation, and controlled-environment agriculture possess relatively established operational foundations. Mycorrhizal applications and drought-response compounds require context-specific field validation. Weather modification remains dependent on suitable atmospheric conditions and presents substantial difficulties in attributing changes in precipitation directly to intervention. It should therefore be treated as a supplementary measure rather than a substitute for conservation, storage, reuse, and drought planning.

Overall, the study concludes that modern technology is an important but conditional instrument for strengthening water and food security. Technology alone cannot overcome weak governance, inadequate infrastructure, limited technical capacity, environmental degradation, or unequal access. Its effectiveness depends on integrated policy, scientific evidence, institutional coordination, human-resource development, financing, environmental safeguards, and adaptation to local conditions.

For Algeria and other North African countries, the most appropriate pathway is not the direct replication of foreign models. International experience should instead be used to identify adaptable principles and technologies that correspond to local climatic, agricultural, economic, and institutional conditions. A diversified portfolio combining wastewater reuse, efficient irrigation, desalination, agricultural digitalization, biological innovation, conservation, and demand management offers a more resilient strategy than dependence on any single technological solution.

Because the study is based on purposively selected documentary cases, its conclusions should be interpreted as a structured qualitative synthesis rather than a statistical assessment of technological effectiveness. Future research should compare verified costs, energy requirements, environmental consequences, distributional effects, and long-term performance through primary data and locally implemented pilot projects.

7. Recommendations

1. Adopt an integrated water–food security strategy. Water, agriculture, food, energy, climate, and environmental policies should be coordinated within a unified national framework.
2. Prioritize water-demand management. Improving irrigation efficiency, reducing leakage, controlling evaporation, and encouraging responsible consumption should accompany investment in new supply.

3. Expand safe wastewater treatment and reuse. Treated wastewater should be incorporated into agricultural and industrial water policies according to clearly defined quality standards and intended uses.
4. Apply a fit-for-purpose reuse model. Treatment requirements should differ according to whether water is intended for industrial processes, restricted irrigation, food crops, groundwater recharge, or human consumption.
5. Strengthen monitoring and public-health protection. Reuse programs should include continuous testing for pathogens, salinity, heavy metals, chemical residues, and emerging contaminants.
6. Develop sustainable desalination capacity. Desalination projects should emphasize energy efficiency, renewable-energy integration, affordability, and environmentally responsible brine management.
7. Pilot emerging technologies before scaling. Electrochemical desalination, weather modification, drought-response compounds, and novel biological treatments should undergo independent local testing before major investment.
8. Modernize agricultural irrigation. Soil-moisture sensors, precision irrigation, remote sensing, automated scheduling, and climate-information services should be introduced according to farm size and crop requirements.
9. Support climate-resilient agriculture. Research should prioritize drought- and salinity-tolerant crops, soil-water conservation, beneficial microorganisms, crop diversification, and locally appropriate production systems.
10. Expand protected and soilless cultivation selectively. Greenhouses, hydroponics, vertical farming, and closed-environment systems should be assessed according to water savings, energy requirements, crop value, and market feasibility.
11. Build national technological capacity. Technology-transfer agreements should include professional training, maintenance, local adaptation, knowledge sharing, and participation by universities and research institutions.
12. Invest in human resources. Water managers, agricultural specialists, farmers, technicians, and policymakers should receive continuous training in digital tools, water quality, system maintenance, and environmental risk management.
13. Ensure equitable access for small farmers. Public financing, credit facilities, cooperatives, shared equipment, extension services, and rural connectivity should prevent technological exclusion.
14. Strengthen institutional coordination. Water agencies, agricultural authorities, universities, municipalities, private companies, farmers, and civil society should participate in planning and evaluating technological interventions.
15. Establish a national water-data platform. Integrated information on rainfall, groundwater, reservoirs, water quality, irrigation, drought, agricultural production, and consumption should support evidence-based decisions.
16. Protect groundwater resources. Abstraction should be monitored, licensed, and aligned with renewable recharge rates, particularly in regions dependent on vulnerable aquifers.
17. Require environmental and life-cycle assessment. Projects should be evaluated according to energy use, emissions, waste generation, ecosystem effects, public-health risks, and long-term operating costs.
18. Use transparent evidence in investment decisions. Promotional performance claims should not replace peer-reviewed research, independent pilot testing, and verified operational data.
19. Promote regional North African cooperation. Countries facing similar water scarcity should cooperate in desalination research, wastewater reuse, drought monitoring, agricultural innovation, and specialist training.
20. Expand empirical research. Future studies should use field experiments, cost-benefit analysis, life-cycle assessment, longitudinal monitoring, and comparative pilot projects to determine which technologies offer the greatest sustainable benefit under local conditions.

Ethics Approval

This study was based exclusively on publicly available academic publications, institutional reports, policy documents, and comparative international cases. It did not involve human participants, animals, personal data, interviews, surveys, or experimental procedures. Therefore, approval from an institutional ethics committee was not required.

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Conflict of Interest

The authors declare that they have no financial, professional, institutional, or personal conflicts of interest that could have influenced the design, analysis, interpretation, or presentation of this study.

Author Contributions

Faiza Belabed, Meryem Laidi, Fatima Zohra Moulefera, and Abdelhakim Ben Salem contributed to the conceptualization, literature review, methodological design, documentary analysis, comparative interpretation, and preparation of the manuscript. All authors critically reviewed the manuscript, approved its final version, and accept responsibility for the integrity and accuracy of the work.

Data Availability

No original datasets were generated or analyzed in this study. All evidence supporting the analysis was obtained from publicly available academic, legal, policy, and institutional sources identified in the reference list.

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Use of Artificial Intelligence Tools

Generative artificial intelligence tools were used only to support language editing and improve the clarity, organization, and readability of the manuscript. The authors reviewed and verified the final text and assume full responsibility for its accuracy, originality, citations, interpretations, and conclusions. Artificial intelligence tools were not used as authors or to generate, fabricate, or manipulate research data.

Research Integrity Statement

The authors confirm that this manuscript represents original scholarly work, has not been published previously, and is not under consideration by another journal. All ideas, evidence, and materials derived from other sources have been appropriately acknowledged and cited. The authors further confirm that no data, sources, findings, or citations were knowingly fabricated, falsified, or misrepresented.

Ethical Approval

This study is based exclusively on the analysis of published texts, documentary and archival sources, and secondary literature. It does not involve human participants or animal subjects, and therefore ethics committee approval was not required. All sources are cited in accordance with academic integrity and copyright principles.

Informed Consent

Not applicable.

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The authors declare that no generative artificial intelligence (AI) or AI-assisted technologies were used in the design of the study, data collection, analyses, or interpretation of the scientific content of this manuscript. Any language-editing support was reviewed and verified by the authors, who take full responsibility for the content of the published article.

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Genişletilmiş Özet

Giriş

Su güvenliği ve gıda güvenliği; iklim değişikliği, nüfus artışı, kentleşme, çevresel bozulma ve doğal kaynaklar üzerindeki baskının arttığı günümüzde birbiriyle yakından ilişkili kalkınma öncelikleri hâline gelmiştir. Su; içme ve kullanma gereksinimlerinin yanı sıra tarımsal üretim, gıda işleme, sanayi, enerji ve ekosistemlerin devamlılığı açısından vazgeçilmezdir. Özellikle tarımın küresel tatlı su kullanımındaki yüksek payı, su kaynaklarında yaşanan azalmanın doğrudan doğruya gıda üretimini, kırsal geçim kaynaklarını, ürün fiyatlarını ve ülkelerin ithalata bağımlılığını etkilemesine neden olmaktadır. Bu sorunlar, yağışların düşük ve değişken, buharlaşmanın yüksek ve yenilenebilir tatlı su kaynaklarının sınırlı olduğu Kuzey Afrika gibi kurak ve yarı kurak bölgelerde daha belirgindir. Geleneksel su temini ve tarımsal üretim yöntemlerinin mevcut baskılara tek başına cevap verememesi, modern teknolojileri stratejik bir seçenek hâline getirmiştir. Atık suyun arıtılması ve yeniden kullanılması, deniz suyunun tuzdan arındırılması, hassas sulama, uzaktan algılama, biyoteknoloji, kontrollü ortam tarımı, buharlaşmanın azaltılması ve kuraklık izleme sistemleri bu kapsamda öne çıkmaktadır. Bu çalışmanın amacı, modern teknolojilerin su ve gıda güvenliğini güçlendirmedeki rolünü seçilmiş öncü uluslararası deneyimler üzerinden incelemektir. Araştırmada modern teknoloji, su güvenliği ve gıda güvenliği kavramları açıklanmış; teknolojik uygulamaların su arzı, kullanım verimliliği, tarımsal dayanıklılık ve üretim devamlılığı üzerindeki katkıları değerlendirilmiştir. Ayrıca söz konusu deneyimlerin gelişmekte olan ülkelere, özellikle Kuzey Afrika ülkelerine aktarılabilirliği; finansman, yönetişim, teknik kapasite, çevresel güvenlik ve yerel koşullara uyum bakımından tartışılmıştır.

Yöntem

Çalışmada nitel, betimsel-analitik ve karşılaştırmalı bir araştırma deseni benimsenmiştir. Araştırma, bütünleştirici literatür incelemesini nitel doküman analizi ve seçilmiş uluslararası deneyimlerin yapılandırılmış karşılaştırmasıyla birleştirmiştir. Kavramsal bölümde modern teknoloji, su güvenliği, gıda güvenliği, sürdürülebilirlik ve teknoloji transferine ilişkin akademik yayınlar, hukuki belgeler, politika metinleri ve kurumsal raporlar incelenmiştir. Uygulamalı bölümde ise Çin, Amerika Birleşik Devletleri, Belçika, Hindistan, Japonya, Suudi Arabistan ve Birleşik Arap Emirlikleri'ndeki teknolojik deneyimler değerlendirilmiştir. İncelenen uygulamalar; hava modifikasyonu, atık su arıtma ve yeniden kullanma, mikoriza ve diğer biyolojik yöntemler, bitkilerin kuraklığa dayanıklılığını artıran bileşikler, rezervuarlardaki buharlaşmanın azaltılması, su tasarruflu donanımlar, elektrokimyasal tuzdan arındırma, hassas tarım, akıllı sulama ve kontrollü ortam üretimi olarak sınıflandırılmıştır. Her vaka aynı analitik sorular çerçevesinde incelenmiştir: Teknoloji hangi su veya gıda güvenliği sorununa cevap vermektedir? Hangi mekanizma aracılığıyla çalışmaktadır? Uygulama için hangi altyapı, finansman, uzmanlık ve düzenlemeler gerekmektedir? Bildirilen sonuçlar nelerdir? Hangi riskler ve sınırlılıklar bulunmaktadır? Deneyim gelişmekte olan ülkelere hangi koşullarda aktarılabilir? Veriler standartlaştırılmış bir çözümleme matrisi yardımıyla sınıflandırılmış; vakalar su arzını artırma, kaliteyi geliştirme, kayıpları azaltma, tarımsal su verimliliğini yükseltme ve iklim dayanıklılığını güçlendirme boyutlarında karşılaştırılmıştır. Kaynaklar kanıt güçlerine göre eleştirel biçimde değerlendirilmiş, özellikle hava modifikasyonu ve deneysel teknolojilere ilişkin performans iddiaları ihtiyatla yorumlanmıştır. Araştırmada insan katılımcı, anket, görüşme veya deneysel veri kullanılmamıştır.

Bulgular

Karşılaştırmalı inceleme, modern teknolojilerin su ve gıda güvenliğine üç temel yoldan katkı sağladığını göstermiştir. İlk olarak atık suyun arıtılması, yeniden kullanılması ve deniz suyunun tuzdan arındırılması gibi arz odaklı teknolojiler kullanılabilir su kaynaklarını çeşitlendirmektedir. Belçika ve Hindistan deneyimleri, güneş enerjili veya biyolojik sistemlerin özellikle tarımsal kullanım için geleneksel olmayan su kaynakları oluşturabileceğini göstermektedir. Bununla birlikte arıtılmış suyun güvenliği; kullanım amacına uygun standartlara, patojen ve kirletici kontrolüne ve sürekli izlemeye bağlıdır. İkinci olarak Japonya'daki su tasarruflu nozullar ve ABD'deki rezervuar uygulamaları gibi verimlilik odaklı teknolojiler tüketimi veya buharlaşma kayıplarını azaltma potansiyeli taşımaktadır. Üçüncü olarak Hindistan ve Birleşik Arap Emirlikleri örnekleri, hassas sulama, sensörler, uydu verileri, dijital platformlar, biyoteknoloji, hidroponik sistemler, dikey tarım ve kontrollü ortam üretiminin tarımsal dayanıklılığı güçlendirebileceğini ortaya koymaktadır. Mikoriza uygulamaları bitkilerin su ve besin maddelerini kullanma kapasitesini artırma potansiyeline sahipken OPABACTIN gibi deneysel bileşikler kuraklık stresinin azaltılmasına yönelik yeni araştırma alanları sunmaktadır. Suudi Arabistan örneği, tuzdan arındırmanın yağıştan bağımsız su arzı sağlayabileceğini; ancak maliyet, enerji kullanımı ve tuzlu atık yönetimi gibi sorunların devam ettiğini göstermektedir. Çin ve ABD'deki hava modifikasyonu uygulamalarının ise uygun atmosferik koşullara ve güvenilir bilimsel doğrulamaya bağlı olduğu belirlenmiştir. Genel olarak teknolojik başarının yalnızca cihaz veya altyapıya değil; yönetişim, finansman, insan kaynağı, bakım kapasitesi, çevresel düzenleme ve yerel uyarlamaya bağlı olduğu sonucuna ulaşılmıştır.

Sonuç

Çalışma, modern teknolojilerin su ve gıda güvenliğini güçlendirmede önemli fakat koşullara bağlı bir araç olduğunu ortaya koymaktadır. Teknolojik uygulamalar kullanılabilir su arzını çeşitlendirebilmekte, su kalitesini iyileştirebilmekte, tüketim ve fiziksel kayıpları azaltabilmekte, kuraklığa karşı dayanıklılığı artırabilmekte ve tarımsal üretimin devamlılığını destekleyebilmektedir. Bununla birlikte hiçbir teknoloji, su ve gıda güvenliği sorunlarını tek başına çözebilecek evrensel bir yöntem değildir. Başarılı ülkeler genellikle atık suyun yeniden kullanılması, tuzdan arındırma, verimli sulama, dijital izleme, kontrollü tarım, biyolojik yenilik ve talep yönetimini bütünleşik bir teknoloji portföyü içinde uygulamaktadır. Gelişmekte olan ülkeler için en uygun yaklaşım, yabancı uygulamaları doğrudan kopyalamak yerine teknolojileri yerel iklim, tarımsal yapı, enerji olanakları, finansman kapasitesi ve kurumsal koşullara göre uyarlamaktır. Özellikle Kuzey Afrika ülkelerinde atık suyun güvenli biçimde yeniden kullanılması, hassas sulamanın yaygınlaştırılması, yeraltı suyu çekiminin denetlenmesi, yenilenebilir enerji destekli tuzdan arındırma ve çiftçilere yönelik dijital danışmanlık hizmetleri önceliklendirilmelidir. Teknoloji transferi yalnızca ekipman satın alınmasıyla sınırlandırılmamalı; eğitim, bakım, bilgi paylaşımı, yerli araştırma ve uyarlama kapasitesini de kapsamalıdır. Ayrıca çevresel etki, yaşam döngüsü maliyeti, halk sağlığı, erişilebilirlik ve küçük üreticilerin teknolojiden yararlanma imkânları değerlendirme süreçlerine dâhil edilmelidir. Araştırmanın seçilmiş dokümanlara dayanan nitel yapısı nedeniyle sonuçlar istatistiksel genelleme sunmamaktadır. Gelecekte yerel pilot uygulamalar, maliyet-fayda analizleri, çevresel yaşam döngüsü değerlendirmeleri ve uzun dönemli saha araştırmalarıyla teknolojilerin gerçek performansı doğrulanmalıdır.