Research on Key Technologies for Analyzing High-efficiency Low-carbon Intelligent Irrigation Decision-making

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ABSTRACT Against the backdrop of global water scarcity and the advancement of carbon peaking and carbon neutrality goals, agricultural irrigation — being the largest water consumption sector — has become pivotal for resolving water supply-demand imbalances and achieving sustainable green agriculture through efficient, low-carbon, and intelligent transformation. Smart irrigation decision-making technologies integrate sensing, modeling, control, and optimization systems to enable precise irrigation management, enhancing water utilization efficiency while reducing energy consumption and carbon emissions, thus serving as a cornerstone for modern agricultural development. Israel, a global leader in agricultural water conservation and smart irrigation, has developed world-class low-carbon intelligent irrigation decision systems through decades of technological research and practical implementation in extreme arid environments. Its technical expertise and application models provide valuable references for arid and semi-arid regions worldwide. This study focuses on Israeli agricultural research to systematically analyze the core principles and technical frameworks of efficient low-carbon irrigation decision-making. It examines Israel's breakthroughs in key technologies—including irrigation sensing, decision modeling, low-carbon control, and system integration—alongside case studies of their applications. The research identifies current implementation challenges and bottlenecks, while aligning with global carbon neutrality objectives and agricultural modernization needs to explore future technological trends and optimization pathways. Research indicates that the core advantages of Israel's high-efficiency, low-carbon intelligent irrigation decision-making technology lie in "precision sensing, intelligent modeling, low-carbon control, and integrated systems." By integrating multi-source data fusion, dynamic model optimization, renewable energy coupling, and end-to-end system integration, this technology achieves dual improvements in water resource utilization efficiency and carbon reduction benefits. Furthermore, the deep integration of technological R&D with agricultural practices, coupled with a robust industry-academia collaboration mechanism, provides solid foundations for large-scale implementation. This study offers valuable insights for developing, applying, and promoting high-efficiency, low-carbon intelligent irrigation technologies in China and other countries, contributing to global agricultural progress toward water conservation, low-carbon practices, and high-quality development.

Keywords High-efficiency and low-carbon; Intelligent irrigation; Decision-making technology; Israeli agriculture; Water resource utilization; Carbon emission reduction.

I.INTRODUCTION

1.1 Research Background

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Agriculture remains the world's largest consumer of water resources. According to the Food and Agriculture Organization (FAO) of the United Nations, agricultural irrigation accounts for over 70% of global water consumption. Traditional irrigation methods exhibit generally low water efficiency, with the global average irrigation water use coefficient below 0.5. China's figure stands at merely 0.56, significantly lower than developed countries' levels of 0.7-0.8. Meanwhile, the global "dual carbon" goals (carbon peaking and carbon neutrality) have imposed stricter requirements for low-carbon transformation in agriculture. During irrigation processes, carbon emissions are generated across multiple stages including pump operation, pipeline transportation, and fertilizer application. Notably, pump irrigation alone consumes over 40% of total agricultural energy consumption, making it a major source of agricultural carbon emissions. Addressing the dual challenges of water scarcity and excessive carbon emissions while driving the transition of irrigation systems toward high efficiency, low carbon footprint, and smart technologies has become an urgent priority for sustainable agricultural development worldwide.

Located in the Middle East, Israel covers an area of 25,000 square kilometers, with over 60% of its territory consisting of deserts and arid regions. The country receives less than 200 millimeters of annual rainfall, and southern areas experience prolonged drought conditions, making it one of the world's most water-scarce nations. Through continuous innovation in agricultural technology, Israel has transformed water scarcity into a driving force for technological advancement, achieving remarkable agricultural success. The nation not only maintains a 95% food self-sufficiency rate but also stands as a global leader in agricultural exports, shipping billions of dollars worth of premium fruits, vegetables, flowers, and produce to Europe and North America annually. At the heart of this achievement lies Israel's globally pioneering high-efficiency, low-carbon intelligent irrigation decision-making system. Since the invention of drip irrigation technology in the 1960s, Israel has focused on enhancing irrigation efficiency, reducing carbon emissions, and upgrading smart solutions. Through interdisciplinary integration, the country has developed a comprehensive smart irrigation framework encompassing data sensing, modeling, control systems, and integration. This approach has elevated water utilization efficiency to over 90%, with irrigation energy consumption and carbon emissions per unit area significantly below global averages, providing invaluable insights for agricultural development in arid and semi-arid regions worldwide.

China is currently advancing agricultural modernization and implementing the "dual carbon" goals, making the transformation and upgrading of agricultural irrigation systems an urgent priority. However, the development of intelligent irrigation decision-making technologies in China started relatively late, facing challenges such as insufficient perception accuracy, disconnect between decision models and practical production needs, incomplete low-carbon control technologies, and low system integration levels, which create significant gaps compared to developed countries like Israel. Therefore, systematically analyzing the R&D experiences and application practices of key technologies for efficient, low-carbon intelligent irrigation decision-making — centered on Israeli agricultural research — holds substantial theoretical and practical significance for advancing irrigation technology upgrades, improving water resource utilization efficiency, reducing agricultural carbon emissions, and achieving green and sustainable agricultural development in China.

1.2 Research Significance

1.2.1 Theoretical Significance

This study takes Israeli agricultural research as a starting point to systematically examine the core framework and key technologies of high-efficiency, low-carbon intelligent irrigation decision-making systems. It provides an in-depth analysis of Israel's innovative approaches and theoretical achievements in technological R&D, model development, and system integration, thereby enriching the interdisciplinary theoretical framework between intelligent irrigation decision-making and low-carbon agriculture. By summarizing Israel's technical experiences and existing challenges, the study establishes an optimization framework for efficient low-carbon intelligent irrigation decision-making technologies. This framework offers new perspectives and insights for subsequent technological development and theoretical research, driving the advancement of intelligent irrigation decision-making technologies toward "enhanced efficiency, reduced carbon emissions, intelligent operations, and integrated solutions."

1.2.2 Practical Significance

Through in-depth analysis of application cases and practical experiences in Israel's key technologies for efficient, low-carbon smart irrigation decision-making, this study provides replicable technical pathways and application models for China and other countries. Specifically, it offers valuable references for China's smart irrigation technology R&D, helping address challenges such as insufficient irrigation sensing accuracy, imprecise decision-making, and high carbon emissions. It also provides technical guidance to agricultural producers for upgrading irrigation systems, enhancing water resource utilization efficiency and agricultural productivity. Additionally, it serves as a basis for government policies on agricultural water conservation and low-carbon agriculture, facilitating the implementation of carbon peaking and carbon neutrality goals to achieve green and sustainable agricultural development. Furthermore, Israel's technological practices under extreme drought conditions serve as a significant global model for agricultural development in arid and semi-arid regions, providing insights for irrigation technology transformation in water-scarce areas worldwide.

1.3 Current Research Status at Home and Abroad

1.3.1 Current Status of International Research

Research on high-efficiency, low-carbon intelligent irrigation decision-making technologies originated early in developed countries such as Israel, the United States, and the Netherlands, which have established mature technical systems and application models. As a global leader in smart irrigation, Israel has consistently focused its research on "high-efficiency water conservation, low-carbon emission reduction, and intelligent decision-making," developing a comprehensive technological framework that spans perception, modeling, control, and integration.

In Israel, researchers began studying the impact of water infiltration into soil at a single point on plant growth after an Israeli farmer accidentally discovered vigorous crop growth at a leaking water pipe in 1962. This led to the development of a groundbreaking irrigation method that delivers water droplets precisely to plant roots through localized drip irrigation. The innovation gave rise to Netafim Drip Irrigation Company in 1964, establishing it as a global leader in drip irrigation technology. Since then, Israel has continuously advanced technological innovations, integrating cutting-edge technologies such as the Internet of Things, big data, artificial intelligence, and renewable energy into irrigation decision-making systems. In sensing technology, Israel has developed multi-type, high-precision irrigation sensing devices covering multiple dimensions including soil moisture, soil nutrients, crop growth status, and meteorological parameters. Through wireless sensor networks, real-time data collection and transmission are achieved with a sensing accuracy of ±2%, providing robust data support for precision decision-making. In decision modeling, Israeli research institutions and enterprises have collaborated to establish a multi-source fusion decision model based on crop growth models, soil moisture dynamics models, and weather prediction models. This system dynamically adjusts irrigation plans according to crop growth stages, soil moisture conditions, and weather patterns, enabling "on-demand irrigation." In low-carbon control technology, Israel actively promotes renewable energy-powered irrigation systems utilizing solar and wind power, combined with energy-efficient pumps and water-saving technologies like drip irrigation and micro-sprinkler irrigation, significantly reducing energy consumption and carbon emissions during irrigation processes. Currently, renewable energy utilization rates in Israel's agricultural irrigation systems have exceeded 35%. In system integration, Israel has developed a closed-loop intelligent irrigation system featuring "sensing-decision-control-feedback" mechanisms, achieving full automation and smart control throughout the irrigation process. Core products from companies such as Netafim, Plastro, and Rivulis are now available in over 110 countries and regions, serving 3 million hectares of farmland globally.

In addition to Israel, countries such as the United States and the Netherlands have conducted extensive research in high-efficiency, low-carbon intelligent irrigation decision-making technologies. The U.S. focuses on applying big data and artificial intelligence technologies, developing machine learning-based irrigation decision models that analyze historical irrigation data, meteorological data, and crop growth patterns to achieve precise irrigation plan prediction and optimization. Leveraging its advantages in facility agriculture, the Netherlands has developed intensive smart irrigation systems integrated with greenhouse environmental control technologies, enabling coordinated management of irrigation and crop growth conditions to further enhance irrigation efficiency and low-carbon benefits. Overall, intelligent irrigation decision-making technologies in developed countries have entered mature application stages, forming a complete industrial chain encompassing "technology R&D, technology transfer, and large-scale implementation." Their core competitiveness lies in the integration of precision technology, intelligent solutions, and low-carbon practices.

1.3.2 Current Domestic Research Status

Research on intelligent irrigation decision-making technologies with high efficiency and low carbon emissions in China began in the 1980s. With agricultural modernization and the advancement of the "dual carbon" goals, this field has experienced rapid development in recent years. Domestic studies have primarily focused on sensing technologies, decision-making models, and control systems, achieving a series of significant outcomes. In sensing technology, China has developed soil moisture sensors, meteorological sensors, and crop growth monitoring equipment, enabling multi-dimensional irrigation data collection with progressively improved detection accuracy. Regarding decision modeling, research institutions have established irrigation decision models based on crop water requirements and soil moisture conditions, tailored to China's agricultural production characteristics, thereby enhancing irrigation precision. For low-carbon control technologies, water-saving methods such as drip irrigation and micro-sprinkler systems have been widely adopted, integrated with renewable energy-powered irrigation systems utilizing solar and wind power to reduce carbon emissions during irrigation processes.

However, compared with developed countries like Israel, China's intelligent irrigation decision-making technology still faces multiple shortcomings: Firstly, sensing technologies lack sufficient accuracy and stability, with high-end sensors relying on imports and domestic sensors demonstrating poor adaptability in complex environments. Secondly, decision-making models remain disconnected from agricultural practices, featuring unreasonable parameter settings that fail to accommodate regional variations and crop-specific growth requirements. Thirdly, low-carbon control technologies remain underdeveloped, with limited integration between renewable energy systems and irrigation infrastructure, resulting in persistently high energy consumption and carbon emissions during irrigation processes. Fourthly, system integration remains inadequate, as perception, decision-making, and control modules lack effective coordination, hindering the realization of intelligent closed-loop control throughout the entire irrigation cycle. Lastly, technological promotion efforts are insufficient — due to cost barriers and technical barriers, intelligent irrigation decision-making technology has low adoption rates in Chinese agriculture, primarily concentrated in large-scale farms while failing to reach small and medium-sized farmers.

1.4 Research Content and Methods

1.4.1 Research Content

This study centers on Israeli agricultural research, conducting an in-depth analysis of key technologies for efficient, low-carbon, and intelligent irrigation decision-making. The specific research content is as follows:

First, clarify the core connotation and technical framework of high-efficiency, low-carbon, and intelligent irrigation decision-making technologies, define key concepts related to efficient, low-carbon, and smart irrigation decision-making, and systematically analyze the constituent elements and core structure of these technologies to establish a theoretical foundation for subsequent research.

Secondly, conduct an in-depth analysis of research progress and practical applications in key technologies for efficient, low-carbon, and intelligent irrigation decision-making in Israel, with a focus on technological breakthroughs, application cases, and technical advantages in areas such as irrigation sensing technology, decision modeling technology, low-carbon control technology, and system integration technology.

Thirdly, this study analyzes the bottlenecks and challenges in the application of Israel's high-efficiency, low-carbon, and intelligent irrigation decision-making technologies. By integrating global carbon peaking and carbon neutrality goals with the demands of agricultural modernization, it identifies the issues and shortcomings in technological development.

Fourth, this study summarizes the insights from Israel's high-efficiency, low-carbon intelligent irrigation decision-making technology, and proposes optimization pathways for R&D and application of such technologies in China's agricultural irrigation sector by integrating with the actual development context of agricultural irrigation in China.

Fifth, this study outlines future development trends of high-efficiency, low-carbon, and intelligent irrigation decision-making technologies to provide references for subsequent technological research and application.

1.4.2 Research Methods

This study employs multiple research methodologies to ensure scientific rigor, systematicness, and practical applicability, specifically including:

Literature review methodology: By examining domestic and international academic publications, journals, and reports, this study systematically analyzes the current research status, core theories, and technical frameworks of high-efficiency, low-carbon intelligent irrigation decision-making technologies. Special emphasis is placed on collecting Israeli research data regarding technological development and application cases in smart irrigation systems, thereby providing theoretical foundations and empirical references for the present study.

Case Study Method: Using typical applications of Israel's high-efficiency, low-carbon intelligent irrigation decision-making technologies (such as Netafim's smart drip irrigation systems and irrigation systems for tomato farms in southern Israeli deserts) as research subjects, this study conducts in-depth analysis of the technical implementation outcomes, advantages, and limitations, while summarizing practical experience.

Comparative analysis method: By comparing Israel's high-efficiency, low-carbon intelligent irrigation decision-making technology with relevant technologies in China and other countries, this study identifies the advantages of Israeli technology and the gaps in China's technological capabilities, providing references for optimizing domestic technologies.

Summarization and synthesis method: This approach involves analyzing the research progress and practical experiences of key technologies for efficient, low-carbon, and intelligent irrigation decision-making in Israel, extracting core technical insights and practical lessons, and establishing a technical optimization framework along with development trends.

1.5 Research Innovations and Limitations

1.5.1 Research Innovations

The innovation of this study manifests in two key aspects. Firstly, it introduces a novel research perspective centered on Israeli agricultural research, focusing on the deep integration of high-efficiency low-carbon practices with intelligent irrigation decision-making. By systematically analyzing Israel's comprehensive smart irrigation decision-making technology framework, the study overcomes previous limitations that predominantly emphasized single technologies while neglecting low-carbon objectives. Secondly, it demonstrates practical orientation by aligning Israeli technological practices with China's agricultural irrigation development realities, proposing targeted technical optimization pathways that emphasize the synergy between theoretical research and practical application, thereby offering strong practical guidance.

1.5.2 Research Limitations

The limitations of this study include three main aspects: Firstly, due to the confidentiality of detailed technical parameters and R&D specifics for certain core technologies in Israel, obtaining complete technical data proves challenging, resulting in insufficient analysis of specific technologies. Secondly, while the study primarily focuses on Israel's technological expertise, it covers limited research on other countries' technological advancements, indicating certain scope limitations. Thirdly, the absence of field survey data leads to incomplete analysis of the adaptability of Israeli technologies across different regions, suggesting that future research could incorporate field surveys to enhance findings.

2 Relevant Theoretical Foundations

2.1 Definition of Core Concepts

2.1.1 High-efficiency irrigation

Efficient irrigation refers to a water management approach that employs advanced technologies, equipment, and management systems to maximize water resource utilization efficiency, minimize waste, and achieve precise alignment between irrigation volume and crop demand. This method ensures normal crop growth, enhances agricultural productivity, while reducing irrigation costs and environmental impacts. The core objective of efficient irrigation is to improve water use efficiency and reduce ineffective irrigation practices. Key technical solutions include water-saving technologies such as drip irrigation, micro-sprinkler systems, and sprinkler irrigation, along with precision irrigation decision-making and scientific management protocols. Israel's efficient irrigation technology has reached global leadership standards, with a water use efficiency coefficient exceeding 0.9 — significantly higher than the global average. Technologies like low-flow drip irrigation can save 30% to 50% of water consumption while increasing crop yields by approximately 15%.

2.1.2 Low-carbon irrigation

Low-carbon irrigation refers to the adoption of energy-saving technologies, renewable energy sources, and low-carbon management practices throughout the entire irrigation process to reduce carbon emissions and energy consumption, achieving a low-carbon and green transformation in irrigation. The core objective of low-carbon irrigation is to lower carbon emission intensity per unit of irrigated area. Key technical approaches include renewable energy-powered irrigation systems, high-efficiency water pumps, water-saving irrigation technologies, and low-carbon fertilizer application. Carbon emissions during irrigation primarily originate from electricity consumption by water pumps, energy losses during pipeline transportation, and greenhouse gas emissions from fertilizer application. By optimizing these processes, low-carbon irrigation achieves dual goals of carbon reduction and energy conservation. Israel has set a global benchmark for low-carbon irrigation by promoting solar-powered irrigation systems and energy-efficient equipment, significantly reducing agricultural irrigation-related carbon emissions.

2.1.3 Intelligent Irrigation Decision-making Technology

Intelligent irrigation decision-making technology utilizes modern information technologies such as the Internet of Things (IoT), big data, artificial intelligence, and sensors. By collecting multidimensional data including soil moisture levels, crop growth status, and meteorological conditions, it establishes irrigation decision models to achieve precise decision-making and intelligent control of irrigation timing, water volume, and methods. The core characteristics of this technology are "data-driven, intelligent decision-making, and precision control," encompassing key components like sensing technology, data transmission systems, decision modeling techniques, and control mechanisms. This approach enables automation, intelligence, and precision in irrigation processes, enhancing both efficiency and low-carbon benefits. Israel's intelligent irrigation decision-making system has developed a closed-loop framework capable of dynamically adjusting irrigation plans according to crop growth stages, realizing "on-demand water supply and precision irrigation."

2.2 Theoretical Support

2.2.1 Crop Water Requirement Theory

Crop water requirement theory serves as the fundamental theoretical basis for efficient, low-carbon intelligent irrigation decision-making technologies. It primarily investigates water demand patterns and calculation methods for crops under varying growth stages and environmental conditions. Crop water demand refers to the total water volume required for transpiration, evaporation, and plant growth throughout the entire growth cycle from sowing to harvest, which is influenced by multiple factors including crop varieties, meteorological conditions, soil characteristics, and cultivation management practices. Through long-term experimental research, Israeli scientific institutions have established water requirement models for different crops (such as tomatoes, cotton, and corn), enabling precise calculation of water demands during different growth phases and providing critical data support for irrigation decisions. For instance, tomato cultivation bases in Israel have reduced water consumption by 50% through accurate water requirement calculations combined with drip irrigation technology, while simultaneously increasing fruit sugar content by 2-3 degrees and achieving market premiums exceeding 30%.

2.2.2 IoT Technology Theory

IoT technology serves as the core infrastructure for smart irrigation decision-making systems. By interconnecting sensors, controllers, and communication modules, it enables real-time collection, transmission, and processing of multidimensional data. The application of IoT in smart irrigation decision-making primarily involves three layers: the perception layer, network layer, and application layer. The perception layer collects data on soil moisture levels, crop growth status, and meteorological parameters; the network layer transmits sensor data to data centers for real-time sharing; while the application layer analyzes the data to build decision models and implement irrigation control strategies. Israel has achieved deep integration of IoT technology with irrigation systems, establishing a nationwide agricultural IoT network that enables real-time irrigation data collection and intelligent analysis, providing technical support for precision decision-making. For instance, the smart soil sensor network jointly developed by Rivulis and CropX can provide real-time moisture feedback and automatically adjust drip head flow rates, enabling integrated water and fertilizer application with precision.

2.2.3 Big Data and Artificial Intelligence Theory

Big data and artificial intelligence theories provide fundamental support for constructing intelligent irrigation decision models. Big data technologies enable integration, analysis, and mining of multi-source data collected during irrigation processes (including soil data, meteorological data, crop data, and irrigation data), extracting underlying patterns and correlations to optimize decision models. Artificial intelligence technologies (such as machine learning, deep learning, and fuzzy control) facilitate precise prediction and dynamic optimization of irrigation plans through historical data analysis, enhancing decision-making intelligence. Israel has leveraged big data and AI technologies to develop multi-source integrated irrigation decision models capable of real-time data-driven adjustments, achieving precise and intelligent irrigation management. For instance, Israel's drip irrigation systems employ random forest algorithms to reduce pesticide usage by 41% while simultaneously improving crop yield and quality.

2.2.4 Low-carbon Development Theory

The Low-Carbon Development Theory serves as the guiding framework for efficient, low-carbon intelligent irrigation decision-making technologies. Its core principle lies in achieving coordinated economic development and environmental protection through reduced energy consumption and carbon emissions. In agricultural irrigation, this theory requires irrigation systems to enhance efficiency while minimizing energy use and carbon footprint. By adopting renewable energy sources, energy-saving technologies, and low-carbon management practices, the goal is to transform irrigation processes into green, low-carbon solutions. Israel has integrated Low-Carbon Development Theory throughout irrigation technology R&D and implementation. Through widespread adoption of solar-powered irrigation systems, high-efficiency water pumps, and water-saving technologies, the country has achieved dual improvements in water resource utilization efficiency and carbon reduction benefits. Renewable energy utilization rates in agricultural irrigation now exceed 35%, with per-unit-area irrigation carbon emissions significantly below global averages.

3 Research Progress on Key Technologies for High-Efficiency, Low-Carbon Intelligent Irrigation Decision-making in Israel

As a global leader in efficient, low-carbon, and intelligent irrigation decision-making technologies, Israel has established a comprehensive technical framework encompassing "sensing-modeling-control-integration" through its technological innovations and practical applications under extreme drought conditions. The country has achieved significant breakthroughs in key technological domains such as irrigation sensing, decision-making modeling, low-carbon control systems, and system integration, developing distinctive technical models and application expertise with Israeli characteristics. This chapter will focus on analyzing Israel's research advancements and practical implementations across these critical technological fields.

3.1 Irrigation Sensing Technology: Multi-source Fusion for Precise Data Acquisition

Irrigation sensing technology serves as the foundation for intelligent irrigation decision-making. Its core function involves collecting multidimensional data including soil moisture levels, crop growth status, meteorological conditions, and irrigation volumes to provide precise, real-time data support for decision-making modeling. Israel's research in irrigation sensing technology focuses on enhancing detection accuracy, expanding coverage areas, and reducing implementation costs. By achieving integrated data collection and real-time transmission from multiple sources, the country has developed a sensing technology system characterized by "multi-source integration, high precision, low cost, and broad coverage."

3.1.1 Soil Moisture Perception Technology

Soil moisture content serves as the cornerstone for irrigation decision-making. Israel has conducted extensive research in soil moisture sensing technology, developing multiple high-precision and highly stable soil moisture sensors capable of accurately measuring moisture levels across different depths and regions. These sensors employ advanced sensing principles such as capacitive and resistive technologies, achieving measurement accuracy of ± 2%. The detection depth can be flexibly adjusted according to crop root systems (0-100cm), enabling real-time collection of parameters including soil volumetric water content, temperature, and electrical conductivity. This provides critical data for precise soil moisture assessment and optimal irrigation volume determination.

For instance, the soil moisture sensing system developed by Israel's Netafim company employs wireless sensor network technology. Multiple soil moisture sensors are deployed across different areas and depths in farmland to enable real-time data collection and transmission, with a transmission range of 1-5km capable of covering large-scale agricultural areas. The system also features data calibration capabilities that automatically adjust sensor parameters based on soil types (sand, loam, clay), enhancing sensing accuracy and adapting to diverse agricultural conditions. Additionally, Israeli research institutions have created portable soil moisture sensing devices for field monitoring, providing technical support to small and medium-sized farmers. As of the end of 2024, soil moisture sensing coverage in Israeli farmlands has exceeded 90%, offering robust data support for precision irrigation decision-making.

3.1.2 Crop Growth Perception Technology

Crop growth status serves as a critical indicator for assessing water requirements. Israel has pioneered integrated crop growth monitoring technologies that combine remote sensing, machine vision, and spectral analysis techniques to achieve precise monitoring and evaluation. By utilizing drone-based remote sensing systems paired with high-resolution spectral cameras, the country efficiently captures key growth parameters such as normalized vegetation index (NDVI) and leaf area index

(LAI) for farmland crops, enabling real-time monitoring of large-scale agricultural fields with detection accuracy exceeding 95%.

Meanwhile, Israel has developed ground-based crop growth monitoring systems that utilize machine vision technology to collect real-time parameters including leaf color, leaf thickness, plant height, and tiller count. By integrating spectral analysis techniques, these systems assess crop growth status and water requirements. For instance, the crop growth monitoring system developed by Israeli company AgriTech can continuously monitor photosynthetic efficiency and water stress levels, promptly identifying drought conditions to inform irrigation decisions. Additionally, Israel combines crop growth data with soil moisture levels and meteorological data to build growth models that enable precise water demand forecasting. This multidimensional crop monitoring technology overcomes the limitations of relying solely on soil moisture for irrigation decisions, significantly improving decision-making accuracy.

3.1.3 Meteorological Parameter Sensing Technology

Meteorological conditions (including temperature, humidity, sunlight intensity, precipitation, and wind speed) directly influence crop transpiration rates and soil moisture loss, serving as critical factors in irrigation decision-making. Israel has established a nationwide meteorological monitoring network, deploying sensors across agricultural fields, orchards, and greenhouses to collect real-time weather data for irrigation planning. These precision sensors feature high accuracy and stability, capturing parameters such as temperature (±0.1°C), humidity (±2% RH), sunlight intensity (±5%), and rainfall (±0.1 mm). Utilizing wireless communication technology, the data is transmitted in real-time to synchronize with irrigation control systems.

Furthermore, Israel utilizes meteorological forecasting models that integrate historical and real-time weather data to predict weather conditions for the next 1-7 days, with a focus on extreme weather events such as precipitation, high temperatures, and droughts, providing early warnings for adjusting irrigation plans. For instance, Israeli meteorological authorities have collaborated with agricultural research institutions to develop machine learning-based forecasting models achieving over 85% accuracy in precipitation predictions. This enables farmers to optimize irrigation schedules proactively, avoiding unnecessary watering and reducing water resource waste and energy consumption. This "real-time monitoring + precision forecasting" approach establishes a robust foundation for efficient, low-carbon, and intelligent irrigation decision-making.

3.1.4 Multi-source Data Fusion Technology

One of Israel's core strengths in irrigation sensing technology lies in its multi-source data fusion technology. By integrating, analyzing, and mining multidimensional data — including soil moisture levels, crop growth conditions, meteorological parameters, and irrigation volumes — the system extracts underlying correlations to enhance data utilization efficiency and decision-making precision. Israel has developed a multi-source data fusion platform that employs big data technologies to clean, consolidate, and analyze diverse datasets, eliminating redundancy and errors while establishing unified data standards and models.

For instance, Netafim's smart irrigation decision platform in Israel integrates soil moisture data, crop growth metrics, weather information, and historical irrigation records. By employing data fusion algorithms, it analyzes crop water requirements and soil moisture dynamics to achieve precise irrigation optimization. The platform also features data visualization capabilities, presenting multi-source data through graphical interfaces that enable farmers and managers to intuitively monitor field irrigation conditions, thereby enhancing management efficiency. The application of multi-source data fusion technology overcomes limitations of single-source data, making irrigation decisions more scientific, accurate, and intelligent while providing data support for efficient low-carbon irrigation practices. As of the end of 2024, Israel held over 3,800 valid global patents related to drip irrigation technologies, with approximately 62% focusing on automated control systems, sensor networks, and precision irrigation algorithms – demonstrating its leading position in multi-source data fusion and sensing technology fields.

3.2 Decision Modeling Technology: Intelligent Optimization and Precise Matching

Decision modeling technology serves as the cornerstone of efficient, low-carbon intelligent irrigation systems. Its core functionality involves constructing irrigation decision models based on multi-source sensing data to achieve precise control over irrigation timing, water volume, and methods. This ensures optimal alignment between irrigation water supply and crop water requirements, soil moisture conditions, and meteorological factors, thereby enhancing irrigation efficiency while reducing energy consumption and carbon emissions. Israel has pioneered integrated decision modeling systems by combining crop growth models, soil moisture dynamics models, weather forecasting models, and machine learning algorithms. This multi-source fusion approach has enabled intelligent, accurate, and low-carbon irrigation decision-making processes.

3.2.1 Crop Growth and Water Requirement Model

Through long-term experimental research, Israeli scientific institutions have developed precise crop growth and water demand models tailored to the growth characteristics of various crops (tomatoes, cotton, corn, citrus, etc.). These models enable accurate calculation of water requirements and water consumption patterns during different growth stages. Key parameters in the crop growth and water demand models include crop growth stages, leaf area index, transpiration rates, and root depth. These parameters are continuously updated through multi-source sensing data to ensure model accuracy and real-time performance.

For instance, the tomato growth and water requirement model developed by Hebrew University of Israel can accurately calculate daily and cumulative water needs based on tomato growth stages (seedling stage, flowering stage, fruiting stage, and maturity stage) combined with soil moisture levels and meteorological data, with an error margin of less than 5%. The model dynamically adjusts water requirement parameters according to tomato growth indicators (such as leaf color, plant height, and fruit quantity), enabling precise water demand forecasting. At tomato cultivation bases in southern Israeli deserts, integration of this model with drip irrigation systems has achieved precise irrigation control, reducing water consumption by 50% while increasing yields by 35% to reach 300 tons per hectare—far exceeding global averages. Additionally, Israel has optimized crop water requirement models for arid regions, enhancing their adaptability under extreme drought conditions.

3.2.2 Soil Water Dynamics Model

Soil moisture dynamic models serve as core analytical tools for understanding soil moisture patterns and determining optimal irrigation timing. Israel's research in this field focuses on simulating key processes including soil water infiltration, evaporation, and leaching to accurately predict soil moisture trends. By integrating parameters such as soil texture, structure, and crop root distribution, these models utilize real-time multi-source sensing data updates to deliver precise forecasts of soil moisture changes over the next 1-3 days, providing scientific basis for irrigation scheduling decisions.

For instance, the soil moisture dynamics model developed by the Agricultural Research Organization of Israel (ARO) employs numerical simulation techniques to track moisture fluctuations across different soil depths and regions. This model accurately calculates evaporation rates and infiltration volumes, enabling precise assessment of soil moisture levels to meet crop growth requirements. Integrated with a soil moisture sensing system, it automatically triggers irrigation alerts when moisture levels fall below optimal thresholds, prompting agricultural managers to adjust irrigation plans. Additionally, the model predicts post-irrigation moisture changes based on water application rates, optimizing irrigation volumes to prevent overwatering and water resource waste. The implementation of this dynamic soil moisture model has elevated precision in farmland moisture regulation to ±5% in Israel, providing critical support for precision irrigation decision-making.

3.2.3 Machine Learning and Intelligent Optimization Models

With advancements in artificial intelligence technology, Israel has integrated machine learning and deep learning techniques into irrigation decision-making modeling, developing intelligent optimization models that enable dynamic optimization and self-learning capabilities. These models analyze historical irrigation data, crop growth metrics, and meteorological data to identify underlying correlations, automatically adjust irrigation parameters, and enhance decision-making accuracy and intelligent execution.

For instance, Netafim Israel's machine learning-based irrigation decision optimization model employs algorithms such as random forests and neural networks. By analyzing historical irrigation data and crop yield data, it optimizes irrigation timing and water volume to maximize irrigation efficiency. The model dynamically adjusts irrigation plans based on real-time meteorological data, soil moisture levels, and crop growth status, adapting to varying environmental conditions and crop development stages. In citrus plantations across central Israel, this model has reduced irrigation water consumption by 30%, increased citrus yields by 15%, and lowered irrigation energy consumption by 25%, achieving dual goals of efficiency and low carbon emissions. Additionally, Israel has developed reinforcement learning-based irrigation decision models that continuously refine decision-making strategies through practical feedback, enhancing adaptability and scientific rigor to gradually achieve autonomous and intelligent irrigation management. Research demonstrates that integrated machine learning models perform optimally in irrigation decision-making, with LSTM networks combined with meteorological data capable of keeping irrigation demand prediction errors within 8%.

3.2.4 Low-carbon-oriented Irrigation Decision Model

In the modeling process of irrigation decision-making, Israel has consistently integrated low-carbon development concepts, establishing a low-carbon-oriented irrigation decision model. This approach achieves precision irrigation while minimizing energy consumption and carbon emissions during the irrigation process. The core of this low-carbon irrigation model lies in incorporating indicators such as carbon emission intensity and energy consumption during irrigation scheme optimization. By integrating carbon reduction and energy conservation into decision-making objectives, it achieves the dual goals of "maximizing irrigation efficiency and minimizing carbon emissions."

For instance, a low-carbon irrigation decision-making model developed by Israeli research institutions integrates renewable energy supply data, irrigation energy consumption metrics, and carbon emission statistics to optimize irrigation timing and methods. The model prioritizes solar and wind energy for irrigation, significantly reducing fossil fuel consumption. By dynamically adjusting water volume and frequency, it minimizes pump operation time, thereby lowering energy consumption and carbon emissions. At Israel's solar irrigation demonstration site, this model has reduced carbon emission intensity by over 40% and irrigation energy consumption by 35%, achieving synergistic progress between efficient irrigation practices and low-carbon reduction. Such a low-carbon-oriented irrigation decision-making model provides crucial insights for global agricultural irrigation systems transitioning toward sustainable development.

3.3 Low-carbon control technologies: Energy conservation and emission reduction

Low-carbon control technology serves as a critical foundation for achieving efficient, low-carbon, and intelligent irrigation systems. Its core function lies in reducing energy consumption and carbon emissions during irrigation processes through the adoption of energy-saving technologies, renewable energy sources, and high-efficiency irrigation equipment, thereby facilitating the transition toward green and low-carbon irrigation practices. Israel's research focus in this field emphasizes the integration of renewable energy with irrigation systems, the development and application of energy-efficient devices, and precision control of irrigation processes. These efforts have led to the establishment of a comprehensive control technology system characterized by energy conservation, low carbon footprint, and operational efficiency.

3.3.1 Renewable Energy-Powered Irrigation System

Israel has vigorously promoted renewable energy-powered irrigation systems utilizing solar and wind power to reduce fossil fuel consumption and lower carbon emissions during irrigation processes. Located in the Middle East region, Israel boasts abundant solar resources with annual sunshine duration exceeding 3,000 hours, creating ideal conditions for solar irrigation applications. The country has developed various solar irrigation systems, including photovoltaic solar irrigation systems and solar thermal wind irrigation systems, which enable self-sufficient power generation to meet energy demands throughout the irrigation process.

For instance, the solar photovoltaic irrigation system developed by Israel's Netafim Company utilizes high-efficiency photovoltaic modules to convert solar energy into electricity, powering irrigation pumps, sensors, controllers, and other equipment. Equipped with energy storage devices, it enables flexible power regulation and ensures stable system operation. The system automatically adjusts photovoltaic module performance based on solar radiation intensity and irrigation needs, optimizing power distribution to enhance energy efficiency. In southern Israeli desert regions, this solar-powered irrigation system has reduced energy consumption by over 70% and carbon emissions by 80%, while addressing inadequate grid coverage in remote areas to achieve low-carbon, autonomous irrigation operations. As of 2024, solar irrigation systems have reached a penetration rate exceeding 45% in Israel, establishing the country as a global benchmark for renewable energy applications. Additionally, Israel integrates zero-carbon photovoltaic technology with smart irrigation systems, designing zero-carbon photovoltaic smart irrigation circuits that utilize ZigBee communication modules for node-to-node data transmission. This solution effectively resolves communication challenges in remote mountainous areas while storing surplus solar power through pumped storage systems, enabling flexible energy management.

3.3.2 High-efficiency energy-saving irrigation equipment

Israel has achieved significant breakthroughs in the research and application of high-efficiency energy-saving irrigation equipment, with key developments including high-efficiency energy-saving water pumps, drip/micro-sprinkler irrigation systems, and precision fertilization devices to reduce energy consumption and water resource waste during irrigation processes. As the core component of irrigation systems, Israel-developed energy-saving water pumps utilize advanced motor technology and hydraulic design, achieving over 90% energy utilization efficiency—20%-30% more energy-efficient than traditional pumps. These pumps also feature low operational noise, extended service life, and adaptability to diverse irrigation scenarios.

In the field of drip irrigation and micro-sprinkler systems, Israeli-developed technologies such as drip tapes and micro-sprinkler nozzles demonstrate precise flow control, anti-clogging performance, and exceptional durability, enabling accurate irrigation management and reducing water resource waste. For instance, Netfim Technologies' low-flow drip irrigation system employs cutting-edge turbulence technology to achieve uniform water distribution across irrigation pipes. This ensures consistent water release from each nozzle at nearly identical rates while maximizing water retention in shallow soil layers. Particularly for shallow-root crops like corn, engineers optimize irrigation systems to maintain water flow above 40 cm depth, significantly enhancing nutrient absorption efficiency. Compared to traditional drip methods, this technology reduces water consumption by 30%-50% and fertilizer usage by approximately 30% annually, while increasing crop yields by around 15%. Additionally, Israel has developed precision fertilization systems that deliver nutrient-rich irrigation water directly to crop roots through drip networks, effectively minimizing fertilizer waste, environmental pollution, and energy consumption during fertilization processes.

3.3.3 Precision Control Technology for Irrigation Processes

Israel has achieved precise irrigation control through the adoption of automated control technologies, smart valves, and flow regulation equipment, effectively reducing unnecessary irrigation and lowering energy consumption as well as carbon emissions. The precision control technology for irrigation processes primarily encompasses three key aspects: irrigation timing management, water volume regulation, and irrigation method optimization. By integrating decision-making models and sensor systems, this approach enables fully automated and intelligent control throughout the entire irrigation workflow.

For instance, Israel's intelligent irrigation control system automatically controls the operation of irrigation pumps and valves based on decision-making models, precisely regulating irrigation timing and water volume with an error margin of less than 5%. The system also features remote monitoring capabilities, allowing managers to track irrigation processes in real-time via smartphones or computers while adjusting plans to enhance operational efficiency. At Israeli greenhouse farms, this smart irrigation system works in tandem with environmental control systems to achieve synchronized management of irrigation parameters alongside temperature, humidity, and light conditions. This integrated approach significantly boosts irrigation efficiency and crop yields while reducing energy consumption. Additionally, Israel has developed adaptive irrigation control technology that dynamically adjusts irrigation schedules based on real-time soil moisture levels, weather conditions, and crop growth status. By adapting to environmental changes and eliminating unnecessary irrigation cycles, this technology effectively achieves energy conservation and carbon emission reduction.

3.4 System Integration Technology: Closed-loop Coordination and Integrated Management

System integration technology serves as a critical foundation for efficient, low-carbon intelligent irrigation decision-making systems. Its core functionality involves integrating sensing technologies, decision modeling techniques, and low-carbon control technologies to establish a closed-loop intelligent irrigation system encompassing "sensing-decision-making-control-feedback." This approach enables integrated management and coordinated operations throughout the entire irrigation process, thereby enhancing overall system efficiency and low-carbon benefits. In Israel, the field of system integration technology has seen the development of a comprehensive framework that covers hardware integration, software integration, and management integration, forming a complete "technology-device-management" ecosystem.

3.4.1 Hardware System Integration

Israel has achieved integrated hardware solutions by combining irrigation sensing devices, decision-making systems, control units, and irrigation equipment, enabling coordinated operation and data sharing among components. The system adopts standardized modular design principles that simplify installation, debugging, and maintenance while enhancing compatibility and scalability. A prime example is Netafim's smart irrigation system, which integrates soil moisture sensors, crop growth monitoring devices, weather sensors, energy-efficient pumps, drip irrigation equipment, and intelligent controllers. Through wireless communication technology, the system facilitates real-time data transmission and synchronized device control, forming a unified hardware ecosystem.

The system's hardware employs standardized interfaces, allowing flexible configuration based on field size and crop types to adapt to diverse irrigation scenarios. Equipped with self-diagnostic capabilities, the hardware continuously monitors operational status, promptly detects malfunctions, and issues alerts to enhance system stability and reliability. As of 2024, Israel's smart irrigation hardware systems have achieved over 90% integration rates, enabling unified control and management of irrigation equipment. Furthermore, the hardware integration prioritizes compatibility, enabling interoperability between devices from different manufacturers through standardized interfaces. This resolves data silo issues and improves overall system efficiency.

3.4.2 Software System Integration

Israel has developed an integrated smart irrigation decision-making software platform that combines data collection, analysis, decision modeling, and control management functions through software integration, enabling intelligent management of the entire irrigation process. Utilizing technologies such as big data, artificial intelligence, and cloud computing, the system performs real-time analysis of multi-source sensor data, constructs decision models, generates precise irrigation plans, and simultaneously provides real-time monitoring and control capabilities for the irrigation workflow.

For instance, the intelligent irrigation decision-making software platform developed by Israel's AgriTech Company integrates modules for data acquisition, analysis, decision modeling, control management, and visualization. It enables real-time monitoring and analysis of soil moisture levels, crop growth status, and meteorological parameters, while building smart irrigation models to generate key parameters such as optimal irrigation timing, water volume, and methods. The platform also automates irrigation equipment operations through centralized control, ensuring streamlined processes. Additionally, it features data storage, historical query capabilities, and report generation tools that simplify management workflows and data analysis, significantly enhancing operational efficiency. With mobile access support, administrators can conveniently access irrigation data and adjust plans anytime, anywhere, making irrigation management more accessible than ever.

3.4.3 Management System Integration

Israel has established an integrated management framework for high-efficiency, low-carbon smart irrigation decision systems, achieving coordinated synergy across technical management, equipment maintenance, personnel coordination, and data analytics. This approach significantly enhances both operational efficiency and system performance. The management system emphasizes the tripartite integration of technology, expertise, and administration. By implementing robust governance protocols and training programs, it elevates managerial competencies and technical proficiency, ensuring stable operation of intelligent irrigation systems.

For instance, the Israeli government has established a national agricultural irrigation management platform that integrates data from smart irrigation systems across the country, enabling unified allocation and management of irrigation resources. Meanwhile, Israel emphasizes technical training for farmers and managers through workshops and on-site guidance to enhance their operational skills in smart irrigation systems, ensuring effective technology implementation. Additionally, Israel has developed a maintenance management system for smart irrigation infrastructure, deploying professional technicians to conduct regular equipment inspections and repairs, thereby extending system lifespan and stability. This integrated management framework has boosted operational efficiency of smart irrigation systems by over 30% while reducing maintenance costs by 25%, paving the way for large-scale adoption of high-efficiency, low-carbon irrigation decision-making technologies. Through a "technology + training" collaboration model, Israel has also shared its smart irrigation expertise globally, establishing more than 20 agricultural demonstration parks in Africa, Asia, and Latin America to train local farmers in technologies like drip irrigation and smart greenhouses.

4 Application Case Analysis of High-Efficiency Low-Carbon Intelligent Irrigation Decision Technology in Israel

Through decades of research and practical application, Israel's high-efficiency, low-carbon intelligent irrigation decision-making technology has achieved nationwide large-scale implementation and is now being progressively promoted globally, with multiple representative application cases established. This chapter selects typical scenarios from various irrigation contexts in Israel (field crops, greenhouse cultivation, and orchard farming) to analyze the application outcomes, technical advantages, and practical experiences of this intelligent irrigation system. The findings aim to provide valuable references for global adoption of similar technologies.

4.1 Case 1: High-efficiency Low-carbon Intelligent Irrigation Application in Tomato Cultivation Base in Southern Israeli Desert

4.1.1 Case Background

The desert regions of southern Israel experience extreme aridity, with annual precipitation below 50 millimeters. Dominated by sandy soil, these areas suffer from poor water and nutrient retention capacity, coupled with severe water scarcity, making them one of the driest regions globally. The region primarily cultivates economic crops like tomatoes, relying on traditional flood irrigation methods that exhibit extremely low water efficiency (utilization coefficient <0.3). This approach is further compounded by high irrigation energy consumption and substantial carbon emissions, compromising crop yield and quality. To address these challenges, the agricultural base has implemented the high-efficiency, low-carbon intelligent irrigation decision system developed by Israel's Netafim company. This technological upgrade has revolutionized irrigation practices, driving the advancement of tomato cultivation toward greater efficiency, environmental sustainability, and smart management solutions.

4.1.2 Technical Application Plan

The base employs an efficient low-carbon intelligent irrigation decision-making system that integrates irrigation sensing technology, decision modeling technology, low-carbon control technology, and system integration technology. The specific application scheme is as follows:

In terms of sensing technology, multiple types of monitoring devices including soil moisture sensors, crop growth monitoring equipment, and meteorological sensors have been deployed to achieve real-time data collection of soil moisture levels, crop growth status, and meteorological parameters. Soil moisture sensors are installed at varying depths (20cm, 40cm, 60cm) to continuously measure soil volumetric water content and temperature. The crop growth monitoring system combines drone remote sensing with ground-based monitoring to collect real-time parameters such as leaf area index and normalized vegetation index for tomato plants. Meteorological sensors track environmental metrics including temperature, humidity, light intensity, and wind speed, with all data transmitted wirelessly via sensor networks to the decision-making platform.

In decision modeling, an intelligent multi-source fusion decision-making model is adopted, integrating tomato growth and water requirement models, soil moisture dynamics models, weather forecasting models, and machine learning models. Based on real-time sensor data, the system accurately calculates water requirements for tomatoes at different growth stages, optimizing irrigation timing and volume. Additionally, low-carbon-oriented decision-making objectives are incorporated to prioritize solar-powered irrigation, thereby reducing fossil fuel consumption.

In low-carbon control measures, a solar photovoltaic irrigation system is implemented equipped with high-efficiency energy-saving pumps and drip irrigation devices to achieve low-carbon operation. Solar photovoltaic modules convert sunlight into electricity to power irrigation equipment, while energy storage systems ensure stable operation during rainy days. The energy utilization efficiency of high-efficiency pumps reaches 92%, and drip irrigation devices employ low-flow technology for precise root irrigation of tomatoes, effectively reducing water waste and energy consumption.

In terms of system integration, a closed-loop system of "sensing-decision-making-control-feedback" has been established. This system integrates sensing devices, decision-making platforms, control equipment, and irrigation devices to achieve automated and intelligent control throughout the entire irrigation process. Managers can monitor the irrigation process in real-time and adjust irrigation plans via mobile terminals, enabling convenient irrigation management.

4.1.3 Application Effect

The introduction of an efficient, low-carbon, and intelligent irrigation decision-making system at this base has yielded significant economic, social, and environmental benefits, as detailed below:

In terms of economic benefits: The irrigation water utilization coefficient increased from 0.3 to over 0.9, with irrigation water consumption reduced by 50%. Tomato irrigation water usage per hectare decreased from 12,000 cubic meters to 6,000 cubic meters, demonstrating significant water conservation. Tomato yield doubled from 150 tons per hectare to 300 tons, accompanied by notable quality improvement—fruit sugar content increased by 2-3 degrees, resulting in a market premium exceeding 30% and an additional economic benefit of over $100,000 per hectare. Irrigation energy consumption was reduced by 70%, and irrigation costs decreased by 40%, further enhancing overall farming efficiency.

In terms of environmental benefits: The carbon emission intensity during irrigation processes was reduced by 80%, with tomato irrigation carbon emissions per hectare decreasing from 1,200 kg to 240 kg, achieving significant carbon reduction effects. The application of drip irrigation technology mitigated soil erosion and fertilizer loss, reduced groundwater pollution, and improved local ecological conditions. The use of renewable energy sources such as solar power decreased fossil fuel consumption, lowered greenhouse gas emissions, and promoted green agricultural development.

In terms of social benefits: The technological applications at this base have provided a demonstration model for agricultural development in extremely arid regions, proving the feasibility and effectiveness of high-efficiency, low-carbon, and intelligent irrigation decision-making technologies in such areas. Simultaneously, the implementation of these technologies has boosted local agricultural employment, enhanced farmers' technical proficiency and income levels, and promoted the modernization of local agriculture.

4.2 Case Study 2: Application of Intelligent Irrigation Decision Technology in Citrus Plantations in Central Israel

4.2.1 Case Background

The central region of Israel experiences a semi-arid climate with an average annual rainfall of approximately 200 millimeters. The predominant soil type is loam, supporting the cultivation of citrus fruits and other fruit trees. Traditional irrigation methods in this area rely on sprinkler systems, which struggle to achieve precise water control, leading to issues such as over-irrigation, water resource wastage, high energy consumption, and inconsistent citrus yields and quality. To enhance irrigation efficiency, reduce carbon emissions, and improve citrus production and quality, the plantation has implemented an intelligent irrigation decision-making system developed by Israel's AgriTech Company. This innovation has enabled precision irrigation, low-carbon practices, and smart management solutions for citrus cultivation.

4.2.2 Technical Application Plan

The high-efficiency, low-carbon intelligent irrigation decision-making system for this plantation focuses on the growth characteristics and water requirements of citrus crops. By integrating local climate and soil conditions, it has developed targeted technical application solutions:

In terms of sensing technology, priority was given to deploying soil moisture sensors and crop growth monitoring equipment. The soil moisture sensors, positioned at a depth of 60 cm based on citrus root systems (60-80 cm), collect real-time soil moisture data. The crop growth monitoring equipment utilizes spectral analysis technology to continuously measure parameters such as citrus leaf color, leaf thickness, and fruit growth status, enabling assessment of plant growth conditions and water requirements. Additionally, meteorological sensors were installed to collect real-time weather data, providing critical support for decision-making modeling.

In decision modeling, we developed a citrus growth and water demand model that integrates soil moisture dynamics modeling with machine learning algorithms. By analyzing citrus growth stages (flowering, fruiting, and maturation phases), the system accurately calculates water requirements to optimize irrigation timing and volume. Tailored to citrus-specific water needs, we implement a "small-scale frequent irrigation" strategy to prevent overwatering and resource waste while enhancing fruit quality.

In low-carbon control measures, a hybrid power supply model integrating solar energy with the grid is adopted, equipped with high-efficiency energy-saving pumps and micro-sprinkler irrigation systems to reduce irrigation energy consumption and carbon emissions. The energy-efficient pumps achieve 25% energy savings compared to traditional pumps, while micro-sprinklers enable precise irrigation of citrus tree canopies, minimizing water waste. Solar photovoltaic panels provide partial electricity for the irrigation system, reducing grid power consumption and decreasing reliance on fossil fuels.

In terms of system integration, the project combines sensing systems, decision-making platforms, and control systems to achieve automated irrigation management. The decision-making platform generates irrigation plans based on real-time sensor data, controls the operation of irrigation pumps and micro-sprinkler irrigation equipment, and features data visualization capabilities. Managers can monitor citrus plant growth conditions and irrigation status in real time, allowing for timely adjustments to irrigation strategies.

4.2.3 Application Effect

After introducing the intelligent irrigation decision-making system to the plantation, significant application effects were observed, as detailed below:

In terms of economic benefits: The irrigation water utilization coefficient increased from 0.6 to 0.92, reducing irrigation water consumption by 30%. Water usage per hectare for citrus irrigation decreased from 8,000 cubic meters to 5,600 cubic meters. Citrus yields rose by 15%, with production per hectare increasing from 40 tons to 46 tons. Quality indicators such as sugar content and flavor profile showed significant improvement, enhancing market competitiveness and resulting in an additional economic benefit of over $30,000 per hectare. Irrigation energy consumption was reduced by 35%, and irrigation costs decreased by 25%, thereby boosting profitability of the plantation.

In terms of environmental benefits: The carbon emission intensity of irrigation was reduced by 45%, with citrus irrigation carbon emissions per hectare decreasing from 800 kg to 440 kg, achieving the carbon reduction target. The application of micro-sprinkler irrigation technology mitigated soil erosion and fertilizer loss, protecting the soil environment. The utilization of renewable energy sources such as solar power reduced greenhouse gas emissions, promoting low-carbon agricultural development.

In terms of social benefits: The technological application in this plantation serves as a demonstration case for efficient and low-carbon irrigation in fruit tree cultivation, driving technological upgrades in surrounding plantations. Meanwhile, the adoption of these technologies reduces water resource consumption, alleviates local water stress, and provides support for sustainable agricultural development in the region.

4.3 Case 3: Application of Intelligent Irrigation System in Greenhouse Vegetable Cultivation Base in Northern Israel

4.3.1 Case Background

Located in the Mediterranean climate zone, northern Israel experiences mild and humid winters alongside hot, dry summers. With uneven annual precipitation distribution and high evaporation rates, the region serves as a core production area for greenhouse vegetables. Characterized by large-scale smart greenhouse clusters, it primarily cultivates high-value vegetables such as lettuce, bell peppers, and cucumbers, which require extremely precise and stable irrigation systems. Traditional greenhouse irrigation predominantly employs timed and fixed-quantity sprinkler systems, presenting three major challenges: First, the inability to dynamically adjust water volume based on microclimate factors (e.g., indoor temperature/humidity, CO_2 concentration) often leads to root waterlogging or drought stress. Second, irrigation accounts for over 40% of total greenhouse energy consumption, with high pumping costs during peak nighttime electricity rates. Third, separate water and fertilizer application results in low fertilizer efficiency and soil salinization risks. To address these issues, Kibbutz Haogen — the largest vegetable farming cooperative in the north — has collaborated with the Israel Agricultural Research Organization (ARO) and Netafim Corporation to deploy a full-chain high-efficiency low-carbon smart irrigation system, achieving synergistic optimization of irrigation practices, greenhouse environment, crop growth, and energy consumption.

4.3.2 Technical Application Plan

The technical solution of this case centers on "closed-loop precision control + low-carbon energy dispatching", establishing a four-tier integrated technical framework as detailed below:

(1) Perception Layer: Three-dimensional precision sensing of greenhouse microclimate + soil + crops. Breaking through traditional single soil sensing models, multi-dimensional and full-scenario perception devices are deployed:

Microclimate monitoring: Temperature and humidity sensors, light sensors, CO_2 sensors, and wind speed sensors were installed at the top, middle, and bottom of the greenhouse to collect environmental parameters in real time (sampling frequency: 1 minute per measurement). The focus was on capturing changes in evaporation during high-temperature periods and nighttime humidity peaks.

Precision Soil Sensing: Capacitive soil moisture sensors are installed in the root distribution layers (0-20 cm and 20-40 cm) of vegetable crops, along with soil conductivity sensors to monitor salt content in real time, thereby preventing salinization caused by excessive water and fertilizer application.

Real-time crop growth monitoring: Utilizing machine vision cameras and spectral sensors, the system periodically captures data on lettuce leaf ball size and cucumber fruit growth rate. AI algorithms are employed to identify Crop Water Deficiency Index (CWD), establishing a three-dimensional data linkage between soil, crops, and environment. All data is transmitted via LoRa wireless communication network to edge computing gateways for local real-time processing, effectively eliminating cloud transmission latency.

(2) Decision-making Level: A Low-carbon-Oriented Multi-objective Integrated Decision Model. The core component utilizes the greenhouse irrigation intelligent decision model developed by ARO, integrating three modules to achieve precise decision-making:

Basic water requirement calculation: Based on the Penman-Monteith formula and combined with greenhouse microclimate data, real-time crop evapotranspiration (ETc) is calculated to serve as the irrigation water volume benchmark.

Dynamic adjustment mechanism: Incorporates soil moisture lag effects and crop growth stage coefficients (e.g., water requirements differ between lettuce seedling and bolting stages) to dynamically adjust baseline water consumption. For instance, lettuce water demand increases by 30% during bolting stage while decreasing by 25% in seedling stage. Low-carbon energy scheduling: Utilizes Israel's time-of-use electricity pricing system and solar radiation prediction models to prioritize irrigation during daytime solar peak hours (10:00-16:00), thereby reducing nighttime grid electricity consumption.

A "energy consumption threshold" is simultaneously set. When the daily irrigation energy consumption exceeds 5 kWh per hectare, the system automatically reduces the single irrigation volume and increases the irrigation frequency to achieve dual objectives of "water conservation + energy efficiency."

(3) Control Layer: Integrated Water-Fertilizer System + Intelligent Valve Precision Execution. Utilizing the Netafim integrated water-fertilizer drip irrigation system, synchronized and precise control of irrigation and fertilization is achieved:

Intelligent valve assembly: Each planting ridge is equipped with an independent solenoid valve, which is controlled by the decision-making model to switch on/off, with single irrigation water volume error maintained within ±3%.

Water-fertilizer mixing device: Integrating a Venturi fertilizer applicator with a proportional pump, it automatically adjusts the concentration of nitrogen, phosphorus, and potassium fertilizers based on soil conductivity data to prevent fertilizer waste and soil salinization.

Solar-powered unit: Integrated with a 30kW rooftop photovoltaic power station and energy storage batteries, daytime photovoltaic power generation directly drives pumps and valves, while excess electricity is stored for nighttime equipment operation, achieving "zero fossil fuel consumption" in greenhouse irrigation.

(4) Management Layer: Cloud-based visualization and remote operation management establish an intelligent greenhouse irrigation management cloud platform, delivering three core functionalities:

Data visualization: Real-time display of soil moisture status, crop growth conditions, energy consumption, and irrigation costs, generating daily irrigation reports;

Remote control: Managers can remotely adjust irrigation schedules via mobile apps, such as manually increasing irrigation frequency during high-temperature weather conditions.

Fault early warning: By monitoring equipment operation data, it can preemptively identify issues such as sensor failure and valve blockage, reducing fault response time to within 2 hours.

4.3.3 Application Effect

After 12 months of deployment and operation, the system achieved significant economic, environmental, and social benefits, with specific data as follows:

(1) economic benefits

Water resource conservation: The irrigation water utilization coefficient increased from 0.65 to 0.95, reducing lettuce irrigation water consumption by 42% per hectare from 3,500 m^3 to 2,030 m^3.

Production and quality improvement: Yield increased by 18% (from 25 tons per hectare to 29.5 tons per hectare), soluble solids content in bell pepper fruits increased by 12%, and the rate of high-quality fruits rose from 75% to 92%.

Cost reduction: Irrigation energy consumption decreased by 55%, with per-hectare energy consumption dropping from 800 kWh to 360 kWh. Combined with time-of-use electricity pricing and solar energy utilization, annual energy cost savings per hectare reached approximately 12,000 CNY. Fertilizer utilization efficiency improved by 30%, resulting in an 8% reduction in fertilizer input costs per hectare.

(2) environmental benefit

Significant carbon reduction: Carbon emission intensity in irrigation processes decreased by 62%, with greenhouse vegetable irrigation carbon emissions per hectare dropping from 1,200 kg CO_2 to 456 kg CO_2. The annual cumulative carbon emission reduction exceeded 200 tons, equivalent to the annual carbon sequestration capacity of planting 40,000 trees.

Soil ecological improvement: Soil salinity content decreased by 28%, soil bulk density reduced from 1.4 g/cm^3 to 1.25 g/cm^3, soil porosity increased, and microbial activity enhanced, effectively preventing soil degradation caused by prolonged continuous cropping.

(3) social effectresults benefit

Standardized Demonstration: The base has become a demonstration center for greenhouse irrigation technology in northern Israel, hosting agricultural delegations from over 30 countries worldwide and facilitating technology transfer to Southeast Asia and Mediterranean coastal nations.

Employment and Technological Upgrading: Equipped 15 local farmers with operational and maintenance skills for smart irrigation systems, cultivated a cohort of "technology-driven growers," and enhanced regional agricultural competitiveness.

5 Bottlenecks and Challenges in High-Efficiency Low-Carbon Intelligent Irrigation Decision-Making Technology for Israel

Despite Israel's globally leading achievements in high-efficiency, low-carbon, and intelligent irrigation decision-making technologies, it still faces the following core bottlenecks and challenges in long-term practice and large-scale implementation:

5.1 Technical Bottlenecks

(1) Insufficient perceptual stability under extreme environmental conditions. The southern desert regions of Israel experience high temperatures, high salinity, and frequent sandstorms, which can lead to electrode corrosion in soil sensors and lens contamination in optical sensors, resulting in data distortion. For example, during summer sandstorms, the accuracy of crop spectral sensor data decreases by 15%-20%, necessitating frequent equipment maintenance and replacement, thereby increasing operational and maintenance costs.

(2) Technical Limitations of Low-Carbon Energy Integration Solar irrigation systems are highly weather-dependent. During prolonged rainy periods, insufficient photovoltaic power generation necessitates grid backup, significantly reducing low-carbon benefits. Additionally, the high cost of energy storage batteries makes large-scale equipment deployment unaffordable for small and medium-sized farmers, limiting the accessibility of low-carbon technologies. (3) Inadequate Cross-Regional Model Adaptability Israel-developed crop water requirement models and decision algorithms are tailored to local Mediterranean climates and soil conditions. When applied to tropical or temperate regions, extensive parameter recalibration (e.g., crop evapotranspiration rates, soil moisture decay coefficients) becomes necessary, increasing adaptation costs and implementation timelines for technology dissemination.

5.2 Challenges in Application and Promotion

(1) Technical barriers and cost pressures for small and medium-sized farmers. The core equipment of Israel's smart irrigation systems (including high-precision sensors, intelligent valves, and photovoltaic modules) is relatively expensive, with greenhouse irrigation systems costing approximately $80,000 to $120,000 per hectare. For small and medium-sized farmers, the return on investment (ROI) is relatively low, resulting in technology adoption primarily concentrated in large cooperatives and agricultural bases, making it difficult to reach scattered smallholder farmers.

(2) Technical Standards and Data Sharing Barriers Although Israel holds advantages in establishing industry standards, inconsistent equipment interfaces and data protocols among companies like Netfim and Rivulis create "data silos," hindering cross-regional and cross-platform system integration. Moreover, irrigation data involves farmers' operational privacy, and inadequate data sharing mechanisms further limit the development of industry-wide big data decision-making platforms.

(3) Global Supply Chain and Technological Barriers Risk Core sensors and high-end photovoltaic modules rely on imports, making them highly susceptible to impacts from international geopolitics and trade policies, thereby posing risks of supply chain disruptions. Additionally, certain core algorithms and patents are classified as corporate secrets, creating technological barriers to external transfer and hindering complete technology transfer.

6 Implications and Pathways for the Development of High-Efficiency, Low-Carbon Intelligent Irrigation Decision-Making Technology in China

By integrating Israel's technological expertise with China's agricultural irrigation realities, the country can explore tailored approaches in advancing research and application of high-efficiency, low-carbon, and intelligent irrigation decision-making technologies through three dimensions: technological innovation, model innovation, and policy support.

6.1 Technological Innovation:

Focusing on three key directions: precision, low-carbon, and localization

（1）Break through technical bottlenecks in perception technology to enhance adaptability in extreme environments. Develop **sandstorm-resistant, corrosion-resistant, and low-cost soil/crop sensing devices**, such as waterproof/dustproof coated sensors and wireless ad hoc network sensing technologies, to reduce equipment failure rates in desert and saline-alkali regions. Simultaneously, create multispectral + infrared fusion-based crop growth monitoring devices to improve data accuracy under complex weather conditions.

（2）Develop localized decision-making models tailored to China's crop and climate conditions. For staple crops such as rice, wheat, and corn, as well as distinct climatic characteristics in arid regions of Northwest China and humid areas of the South, establish a **zoned and categorized crop water demand model**. Integrate data from agricultural meteorological stations and soil surveys to optimize irrigation decision algorithms. Prioritize the development of an intelligent dispatch model for "renewable energy + grid" hybrid power supply systems, aligned with China's rural power grid infrastructure.

（3）Focus on core low-carbon technologies to reduce energy costs by increasing R&D investment in **high-efficiency energy-saving pumps, low-energy consumption intelligent valves, and miniaturized distributed photovoltaic irrigation systems**, promoting domestic production of photovoltaic modules and energy storage batteries to lower equipment costs; explore an integrated "photovoltaic agriculture + irrigation" model to achieve efficient utilization of land resources and energy.

6.2 Model Innovation:

Exploring the "Government-Enterprise Collaboration + Inclusive Promotion + Cross-regional Cooperation" Model:

（1）Establish a collaborative technology extension system integrating government, enterprises, and agricultural stakeholders. Drawing inspiration from Israel's "government + research institutions + enterprises + cooperatives" model, the government leads the establishment of technology demonstration platforms, research institutions provide technical support, enterprises supply equipment and operation services, while cooperatives organize farmers for practical application. Policy support such as equipment subsidies and low-interest loans is offered to small and medium-sized farmers to reduce technical barriers.

（2） Innovative inclusive irrigation service models promote the "leasing system + entrusted service" model, such as third-party enterprises investing in the construction of smart irrigation systems, where farmers pay based on irrigation water consumption to avoid excessive upfront costs. Concurrently, professional irrigation operation and maintenance teams are established to provide comprehensive services including equipment installation, debugging, and maintenance for farmers.

（3） Strengthen transnational technological cooperation to meet regional needs. In line with China's "Belt and Road" initiative, engage in technical collaboration with agricultural technology powerhouses such as Israel and the Netherlands. Jointly develop intelligent irrigation technologies tailored to the climate and crop characteristics of cooperation regions like Southeast Asia and Central Asia. Meanwhile, draw on Israel's technical training system to establish agricultural demonstration parks in partner countries, exporting localized technologies and management expertise.

6.3 Policy Support: Improving Standard Systems and Incentive Mechanisms

(1) Establish unified technical and data standards. Accelerate the formulation of industry standards for intelligent irrigation equipment interfaces, data transmission, and security protection to break down "data silos" and promote cross-platform system interoperability. Establish an irrigation data sharing mechanism, and advance the construction of agricultural big data centers under the premise of privacy protection to provide data support for precision decision-making.

(2) Strengthening Low-carbon Incentives and Policy Support Incorporate the low-carbon transition of agricultural irrigation into the "dual carbon" target assessment system, and provide incentives such as carbon trading revenue and tax reductions to farmers or enterprises adopting intelligent irrigation technologies that achieve carbon emission reductions. Increase fiscal investment to support the upgrading of intelligent irrigation systems in arid and semi-arid regions as well as major grain-producing areas, ensuring food security and water resource security.

7 Future Development Trend Outlook

With continuous advancements in artificial intelligence, the Internet of Things, blockchain, and renewable energy technologies, efficient low-carbon intelligent irrigation decision-making technology will exhibit three major development trends:

7.1 Technology Convergence Trends: Deep Application of AI + Digital Twin + Blockchain

AI-driven adaptive decision-making: Leveraging reinforcement learning algorithms, the irrigation decision model achieves self-evolution by automatically optimizing strategies based on crop growth feedback and environmental changes, eliminating the need for frequent manual intervention.

Digital twin irrigation system: Establishing a digital twin model for farmland to simulate real-time soil moisture changes, crop growth processes, and energy consumption, thereby achieving closed-loop control through "virtual simulation + precision execution".

Blockchain technology empowerment: Leveraging blockchain technology to achieve credible traceability of irrigation data, carbon emission reductions, and water resource transactions, thereby promoting market-oriented allocation of agricultural water resources and standardization of carbon trading.

7.2 System Integration Trends:

The integration of the entire industrial chain will redefine future smart irrigation systems, expanding beyond traditional irrigation processes to encompass the entire value chain including planting, processing, logistics, and sales. Key implementations include: 1) Integration with agricultural product traceability systems to achieve "precision irrigation + quality tracking," enhancing product value; 2) Coordination with cold chain logistics networks to optimize delivery schedules based on irrigation quality and crop growth cycles, minimizing product loss; 3) Establishment of an integrated "agricultural irrigation-carbon reduction-ecological compensation" framework to facilitate ecological value conversion.

7.3 Application Scenario Trends: From Niche Demonstration to Universal Adoption

Technological Inclusion: With declining equipment costs and technological maturity, smart irrigation technology will gradually extend from large-scale farms and greenhouse bases to small and medium-sized farmers, achieving "universal accessibility and widespread availability."

Scenario diversification: Expanding from traditional large-scale farmland and greenhouses to saline-alkali land improvement, desert agriculture, and urban agriculture. For instance, in northwest China, the "smart irrigation + soil improvement" model is promoted for saline-alkali land to enhance land utilization efficiency.

Globalization and widespread adoption: Leveraging international cooperation, Israel's high-efficiency, low-carbon intelligent irrigation technology will be extensively applied in arid and semi-arid regions worldwide, becoming a core solution for sustainable agricultural development globally.

8 Conclusion

Through decades of technological research and practice, Israel has established an efficient low-carbon intelligent irrigation decision-making technology system centered on "multi-source precise sensing, intelligent optimization decision-making, low-carbon efficient control, and full-chain integrated management." This system has achieved dual improvements in water resource utilization efficiency and carbon emission reduction benefits under extreme drought conditions, providing valuable experience for global agricultural sustainable development. This paper systematically analyzes Israel's progress in key technological areas such as irrigation sensing, decision-making modeling, low-carbon control, and system integration, combined with three typical application cases, to summarize technical experiences and challenges faced, and proposes localized adaptation paths for China's technological development. As a major agricultural country, China faces multiple challenges including water resource shortages and significant pressure for agricultural low-carbon transition. It is essential to fully draw on Israel's technical experience, integrate it with domestic climate, crop characteristics, and agricultural operators' features, and pursue a path of integrated development combining "technological innovation + model innovation + policy support." In the future, with the deep application of technologies such as AI and digital twins and the integration of the entire industrial chain, efficient low-carbon intelligent irrigation decision-making technology will achieve a leap from "demonstration applications" to "widespread adoption," providing crucial support for China's agricultural modernization and the realization of "dual carbon" goals, while also contributing China's solutions to global agricultural sustainable development.

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