



OPTIMAL WATER-SAVING TECHNIQUES FOR AGRICULTURAL PRODUCTION UNDER CLIMATE CHANGE IN CHINA: A COMPREHENSIVE REVIEW

Li Jing^{1*}, Muhammad Umar Farooq^{2*}, Li Yang³, Anum Rafiq⁴, Aftab Anwar⁵, Ismail Shah⁶,
Muhammad Ameen⁷

Abstract:

As China confronts escalating water scarcity and the profound impacts of climate change, its agricultural sector stands at a critical juncture. This review article underscores the imperative for adopting water-efficient agricultural practices to safeguard national food security and promote sustainable development. It explores the dual challenges of enhancing agricultural productivity and conserving scarce water resources amid pressures from a vast population and climatic variability. The article assesses a range of water-saving techniques, focusing on the development and adoption of drought-resistant and water-efficient crop varieties. It delves into innovative irrigation strategies such as drip, precision, and deficit irrigation, alongside soil water conservation methods like mulching and conservation tillage, which collectively enhance water retention and efficiency. The potential for water recycling and reuse through advanced treatment methods is also examined. This comprehensive analysis advocates for a collaborative approach involving scientists, policymakers, and farmers to foster the adoption of these strategies. The review emphasizes the critical role of ongoing research, technological advancements, and robust policy frameworks in navigating the complexities of water management in agriculture. By addressing these issues, the article aims to contribute to the development of resilient agricultural practices that can withstand the challenges posed by climate change and water scarcity.

Keywords: Water-saving techniques, crop production, climate change, water management, agriculture, China.

^{1,2*,3,7}School of water conservancy, Yunnan Agricultural University, Kunming 650201, China

¹Email: lijing69@ynau.edu.cn; ²enr.umarrao@yahoo.com

^{1,2*,3,7}International Joint R & D Center for Smart Agriculture and Water Security, Yunnan Agricultural University Kunming 650201, P.R. China

⁴State key laboratory of Soil Erosion and Dry land Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A & F University, Yangling, 712100, China

⁵Institute of Mountain Hazards and Environment, CAS, Chengdu, 610041, China

⁶University of Chinese Academy of Sciences, Beijing 100049, China

***Corresponding Author:** Li Jing, Muhammad Umar Farooq

*School of water conservancy, Yunnan Agricultural University, Kunming 650201, China

*International Joint R & D Center for Smart Agriculture and Water Security, Yunnan Agricultural University, Kunming 650201, P.R. China. ¹Email: lijing69@ynau.edu.cn; ²enr.umarrao@yahoo.com

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Introduction:

The conflict of water scarcity, China's agricultural sector stands at the forefront, consuming 65% of the nation's freshwater resources [1]. This consumption is intensified by the dual pressures of a growing population and the varying impacts of climate change, which threaten not only food security but also the economic and environmental sustainability of the nation [2, 3]. With the uneven distribution of water resources compounding regional disparities [4], the need for an efficient and strategic approach to water management becomes paramount. This review aims to dissect these complexities by delving into the Water Footprint (WF) concept—a metric that quantifies the volume of water utilized across agricultural supply chains. In doing so, it seeks to illuminate the pathways through which China can navigate the intricacies of water resource management, thereby safeguarding its agricultural resilience and sustainable development [5, 6]. By examining key hydrometeorological variables and the agricultural water footprint within China's major river zones, this study synthesizes contemporary research findings to propose an integrated framework for

water use optimization and sustainable crop farming practices. It also explores the role of technological advancements in improving water footprint efficiency and how these can inform policy decisions in the context of China's unique environmental challenges [7, 8].

Water scarcity in China's agriculture is addressed by the Water Footprint (WF) concept, which measures the total volume of freshwater used in the manufacturing process. It evaluates direct and indirect water use throughout the supply chain to identify efficiency improvements. China's agricultural WF affects global water resource management and sustainability due to the global nature of food and product supply chains, focusing on the importance of understanding and improving water-intensive practices in China for global conservation. The total agricultural water footprint (TWF) of China, quantified at 1125.6 G m³, delineates the extensive use of water resources, with blue, green, and grey components representing 24.4%, 57.4%, and 18.2% of TWF, respectively [9]. Distribution of China's total agricultural water footprint shown in Fig 1.

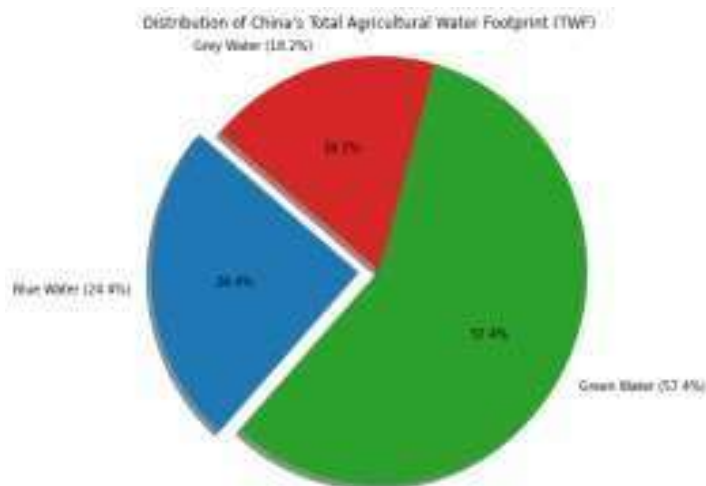


Fig 1. Distribution of China's total agricultural water footprint

This differentiation is vital for evaluating the efficiency and sustainability of water use in crop farming, reflecting advancements in agricultural technology that have gradually improved water footprint efficiency (WFE). The shift in the WF across different regions, notably in Anyang within the North China Plain, underscores the dynamic nature of agricultural water use, driven by factors such as increased agricultural activity and nitrogen consumption, which have led to an uptick in WF_{green}, WF_{blue}, and WF_{grey} [10]. Furthermore, the analysis of agricultural WFs in regions with high agricultural activity, such as the Northeast, the Huanghuai River, the Yangtze

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River Basin, and Northwestern Xinjiang, highlights the influence of economic and technological factors on water use efficiency. These include GDP per capita, investment in fixed assets, and irrigation technology, which collectively shape the agricultural water footprint [11]. Accurately calculating the water footprint by distinguishing between soil evaporation and crop transpiration and considering varied irrigation practices becomes paramount for integrating the agricultural water footprint into broader water resource management and monitoring systems, offering a nuanced approach to optimizing water use in agriculture [7, 12]. This comprehensive

understanding of the water footprint serves as a foundation for developing targeted strategies to mitigate water scarcity and enhance sustainability in China's agricultural sector, providing a benchmark for policymakers and stakeholders in navigating the complexities of water resource management.

Irrigated agriculture in China plays a crucial significance as it sustains agricultural production and job opportunities, but it is additionally contributing to the country's water scarcity [13-15]. The effectiveness of innovative irrigation techniques and soil water conservation methods, explores water recycling strategies, and discusses the role of policy in achieving water security and food sustainability in China [16-18]. It examines the impact of climate change on water resources, the spatial distribution of water scarcity, and the importance of economic viability and policy frameworks in the adoption of water-saving practices [19-21]. By highlighting the agricultural water footprint and efficiency gains from technological advancements, this study presents a thorough analysis of China's efforts to navigate the complexities of agricultural water management in the face of climate change and water scarcity challenges.

The intricate dynamics of water scarcity and the multifaceted challenges it poses to China's agriculture underscore the pressing need for innovative water management strategies as climate Human activities have significantly decreased runoff in water-scarce northern river basins from 1961 to 2018 [22], exacerbating regional water scarcity, which is further complicated by the uneven spatial distribution of China's water resources [23]. To solve these problems, people need to work together on new ways to water crops, keep soils from drying out, reuse water, and think about what these changes might mean for policy. They also need to use precise irrigation and water-saving technologies [24, 25].

Irrigated agriculture in China has been an essential source of rural employment [26] and livelihood for millions, contributing to 75% of the country's total agricultural output. China's rapid economic growth and poverty reduction are closely tied to irrigated agriculture [27]. However, this sector also contributes to the country's water stress. Irrigated agriculture uses over 60% of the nation's water resources, more than any other activity [28]. Population growth, rapid industrialization, and the adverse effects of climate change exacerbate the

problem [29]. Water resource efficiency varies across China, with the highest scores in the east and west and the lowest in the central region. Environmental regulations negatively impact efficiency, as businesses often choose to pay regulatory costs instead of investing in innovation, leading to resource waste [30]. The study examines historical and future trends in vital hydrometeorological variables (precipitation, potential evapotranspiration, and runoff) across 10 major river zones in China [31]. It notes a significant decrease in runoff in water-scarce northern river basins from 1961 to 2018, with variations primarily attributed to human activities [32]. Agriculture is the largest user of freshwater, consuming 70–86% of available water resources globally [33]. The spatial distribution of China's water resources is uneven, exacerbating regional water scarcity [34]. Irrigation water withdrawals in China have shown spatial variation, with the Middle-Lower Yangtze River region and Xinjiang having the highest withdrawals [35]. The increased irrigation water demand has led to unbalanced water budgets and crop water deficits, negatively impacting wheat yields in various regions [36].

Between 1990 and 2018, the agricultural water footprint (WF) in Anyang, North China Plain, changed. The analysis shows an increase in WF_{green}, WF_{blue}, and WF_{grey} due to factors such as increased agriculture and nitrogen consumption. The findings highlight the importance of strong water resource management in improving efficiency and addressing water scarcity, and they provide significant insights for policymakers [10]. Regions with high agricultural water footprints, such as the Northeast, the Huanghuai River, the Yangtze River Basin, and Northwestern Xinjiang, as well as the factors that influence the agricultural water footprint, such as GDP per capita, investment in fixed assets, and irrigation technology [37]. The accuracy of water footprint calculations is determined by distinguishing between soil evaporation and crop transpiration and considering different irrigation practices [38]. The literature also highlights the need to incorporate the agricultural water footprint into water resource management and monitoring systems at the city level [39]. Using four global circulation models, the study predicts that in 2030–2050, climate change will boost yearly water availability by 11–16%. A high rainfall of 27% expected throughout the wet season raises concerns about a 93% spike in peak flows and possible dangers to infrastructure, crops, and

towns. The increasing energy unpredictability and spilled flows, highlighting the pressing need for adaptation strategies [40].

Global rivers affected by flow and dam-related variables forecast massive discharge changes, impacting biodiversity, ecosystems, and human populations due to floods or water shortages. Dam-impacted basins need proactive management of more than one billion people [41]. During droughts, increased vegetation greenness, particularly in forested humid areas, can decrease water yield by 3–27%, emphasizing potential conflicts between ecosystems and human water needs. Implementing targeted afforestation and selective harvesting may mitigate these challenges and maintain water supply [42]. The comprehensive findings offer valuable insights for policymakers, informing climate change adaptation and mitigation strategies to sustain the livelihoods of vulnerable communities in the region [43]. Assessing the vulnerability of water availability to changing climates involves less than 10% precipitation decrease could reduce water availability by 25% due to climate change [44]. The importance of water availability estimation for agriculture, drought monitoring in vulnerable Mediterranean areas for climate adaptation, and precision crop evapotranspiration monitoring with high-resolution EO images [45]. In 2030 and 2050, water availability is projected to rise by 11% and 8% (SSP-RCP 2-4.5) and by 16% and 14% (SSP-RCP 3-7.0). Dry and wet seasons will intensify, concentrating water in the rainy season, with notable increases of up to 26% (February) and 27% (March-April) [40]. Climate models indicate a 93% increase in peak flows, posing infrastructure, agriculture, and urban areas risks [46]. Identifying a research gap in run-of-river small hydropower plant operation optimization [47].

To meet 2050 food demand in the face of water scarcity, emphasis must be placed on water use efficiency (WUE) and crop water productivity (CWP). Strategies must be implemented at both the local and global levels [48]. Adopting precision irrigation and water-saving technologies, including innovative irrigation systems, proves instrumental in enhancing WUE, particularly in rice cultivation [49]. Integrating irrigation techniques with agronomic practices, such as laser land levelling and crop residue management, is crucial for achieving elevated water productivity [50]. To optimize water, use and enhance productivity in cereal-based systems, integrate

improved irrigation scheduling, laser land levelling, water-efficient varieties, seed priming, direct-seeded rice, bed planting, zero tillage, and crop residue management. This approach ensures "more crop per drop" across diverse soil and climate conditions [51]. Moreover, insights from experiences in countries like Israel, Japan, Korea, and Singapore provide valuable perspectives on advanced irrigation technologies, efficient irrigation programs, and stringent water management systems applicable to water-saving agriculture [52].

Efficient irrigation involves assessing crop water needs and implementing water-saving practices. Technologies for rice cultivation, including efficient irrigation systems and agronomic practices, contribute to water conservation. Adopting tools for improved irrigation water efficiency enhances overall water use efficiency [49].

This literature underscores the paramount importance of water-saving techniques in agriculture, particularly in the context of China's changing climate and its implications for water stress and agricultural productivity. The necessity to address these challenges is not just critical for sustaining China's food security but also for ensuring the economic livelihood of millions dependent on agriculture. This review has set out to explore the myriad of strategies and innovations aimed at promoting sustainable agricultural practices and efficient water management strategies. Because irrigated agriculture is a cornerstone of China's food production system, contributing 75% of the total agricultural output, the findings of this review have the potential to significantly impact the development and implementation of policies and practices that can ensure the long-term sustainability of China's water resources and agricultural productivity. The objectives of this review, therefore, extend beyond the academic sphere, aiming to offer actionable insights for policymakers, practitioners, and the agricultural community at large in navigating the challenges posed by climate change and water scarcity.

Methods

In China, drip irrigation increased crop yields by 2.32% to 28.92% over other methods. [53]. When faced with water scarcity, this approach surpasses floods, furrows, sprinklers, or micro-sprinkler irrigation, demonstrating significant yield improvements of 28.92%, 14.55%, 8.03%, 2.32%, and 5.17%, respectively. Increased drip irrigation volumes (100–120%) contributed to these gains.

Notably, the drip irrigation system (DS) not only conserves considerable water (40-54%) but also saves electricity (26-47%), establishing itself as an

effective method for sustainable water use and increased agricultural productivity [54] graphically shown in fig 2.

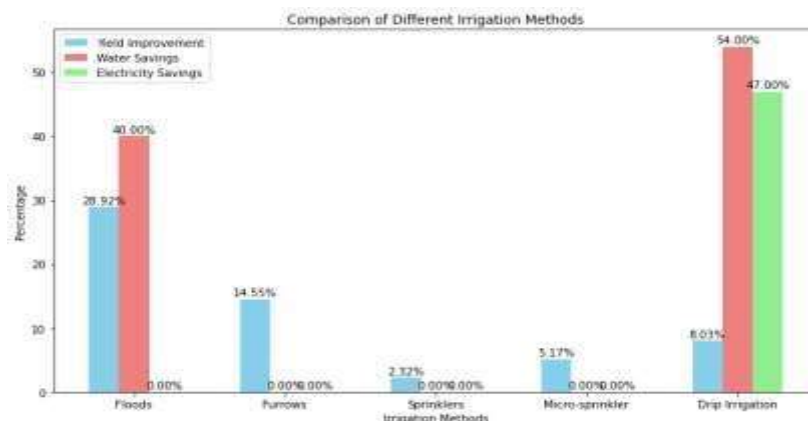


Fig 2. Comparison of different irrigation Methods

The effective utilization coefficient of agricultural irrigation water (EUCAIW) in Jiangsu province rose from 0.59 in 2014 to 0.614 in 2019, signifying increased water-use efficiency. Water-saving technology, implemented on 67.8% of the irrigated arable land in Jiangsu (2.848 million hectares) in 2019, showcases the success of

government initiatives. Despite the need for a multi-party strategy to resolve stakeholder conflicts, the government's water-saving programs can serve as a model for similar changes in other region [55]. Effective Utilization is shown in Fig 3.

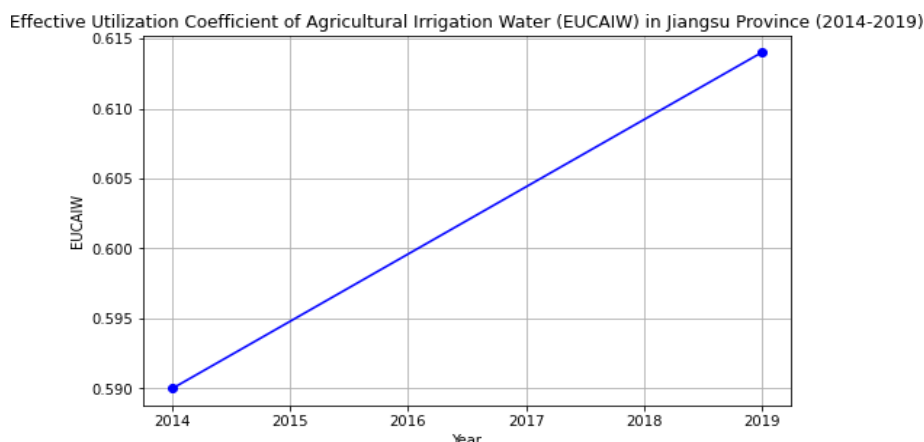


Fig 3. Effective Utilization Coefficient of agricultural irrigation Water in Jiangsu

Encouraging water-saving irrigation practices significantly enhances food crop yields in China, with agricultural input variables like sown area, chemical fertilizer, and mechanical power moderating the effect. The impact is more pronounced in areas with lower precipitation or water-saving irrigation rates, although effectiveness varies by region. In summary, the widespread adoption of water-saving irrigation practices is crucial in ensuring food security in China [56].

Climate change

It is predicted that overall water resources in China will slightly increase due to climate change

between 2021 and 2100, with different rates of increase or decrease in specific river basins [57]. China's agricultural production is impacted by climate change; a study utilizing the DEA-Malmquist Index shows varying results, with the Sichuan Basin excelling at 22.3% TFPC growth and the Qinghai Tibet Plateau exhibiting favorable implications. Regional differences highlight the necessity for customized approaches and confirm the role that climate plays in agricultural output and technological advancements [20]. Environmental Capacity (WEC) by optimizing reservoir operations and amplifying designed low water flow. Greater regulating capacities in water projects minimize WEC variations amidst

changing water availability and demand. A surge in local water demand and limited project regulating capacity can diminish WEC [58]. Despite rising total water resources under the RCP4.5 scenario, uneven distribution and increased demand may lead to heightened water deficits, reducing low water flow and WEC. Climate change policies that are disjointed and reactive put private gain ahead of public good and highlight the vulnerability of the population. Social and physical measures must be implemented in the long run to address climate vulnerability. Politically motivated yet time-bound, short-term interests impede adaptation and put public health last, while limited planners fight to preserve inequality. To ensure equitable community well-being and successful adaptation, it is crucial for climate policy research to include the socio-political consequences [59].

China's Water Consumption Trends

Water consumption in China is expected to rise to 514-717 km³ by 2086-2100, whereas water resources may rise to 989-1032 km³, depending on the scenario. Temperature, animals, and planted area affect agricultural water consumption, which varies among circumstances. Due to demographic trends, household consumption is predicted to fall, while energy-related water demand is diversified [60]. The northwest river basins of China warmed more between 1961 and 2019. Only in these basins did precipitation increase considerably. Global temperatures are expected to climb between 2021 and 2100, with "RCP8.5" predicting considerably greater warming. Precipitation is expected to vary and slow after 2070. Due to

global warming, water resources may increase. Climate change may reduce water resources in the Songhua, northwest, and Yellow River basins and boost them in the Huai, Hai, Yangtze, Pearl, and southeastern basins [61]. The study found that central Shandong Province expects a slight decrease in water irrigation requirements for maize due to climate change, whereas Jiangsu Province expects a 30% increase. Wheat irrigation may be reduced by 3-24% over the North China Plain, except in Shandong and Hebei in the north. Despite unpredictable changes in irrigation demand, crop evapotranspiration is projected to climb substantially from 2021 to 2050. The evaluation suggests strategic adjustments, such as increasing cultivation in the province's central region and expanding agricultural fields in certain places. The need to utilize drought-resistant crop varieties to reduce water use in the face of impending climate change challenges is highlighted [62]. The future trends of China's water consumption and resources from 2021 to 2100. It shows estimated water consumption increasing to between 514 and 717 km³, while water resources are projected to rise to 989 and 1032 km³, depending on various scenarios. The graph captures the significant interactions between climate change, agricultural demands, and demographic trends affecting water consumption and availability in China. It highlights the critical need for strategic adjustments in water management and farming practices in response to these challenges. Highlights of future trends of China's water consumption and resources shown in Fig 4.

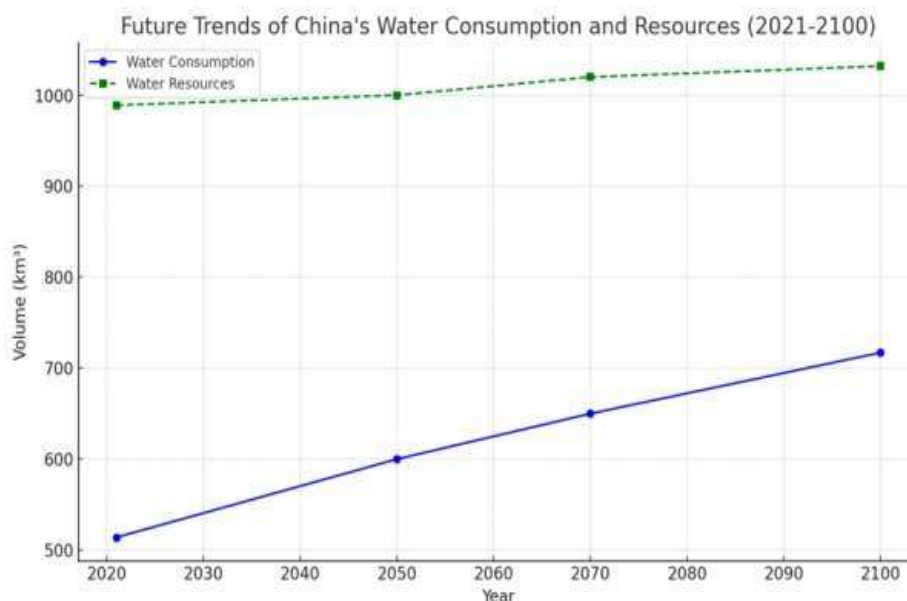


Fig 4. future trends of China's water consumption and resources

Current status of major Chinese crops, particularly their climate change adaptation strategies and measures.

Key strategies for mitigating the effects of climate change on crops in China include the placing of importance of seed security, the optimization of agricultural management practices, and the adoption of advanced adaptation technologies. Seed security assurance is of the utmost importance when it comes to determining crop cultivation areas and ensuring the sustainability of food production. Strategies that target seed security, in particular, are crucial for reducing the

negative effects of climate change on food security.

Agricultural management that is optimized through strategic planning may help save water, enhance efficiency, and improve seed and food production [63]. Agricultural water conservation in irrigated areas is crucial for enhancing efficiency, reducing conflicts, ensuring water security, and fostering sustainable agricultural development [64]. By using different irrigation methods increase in crop yield shown in Fig 5.

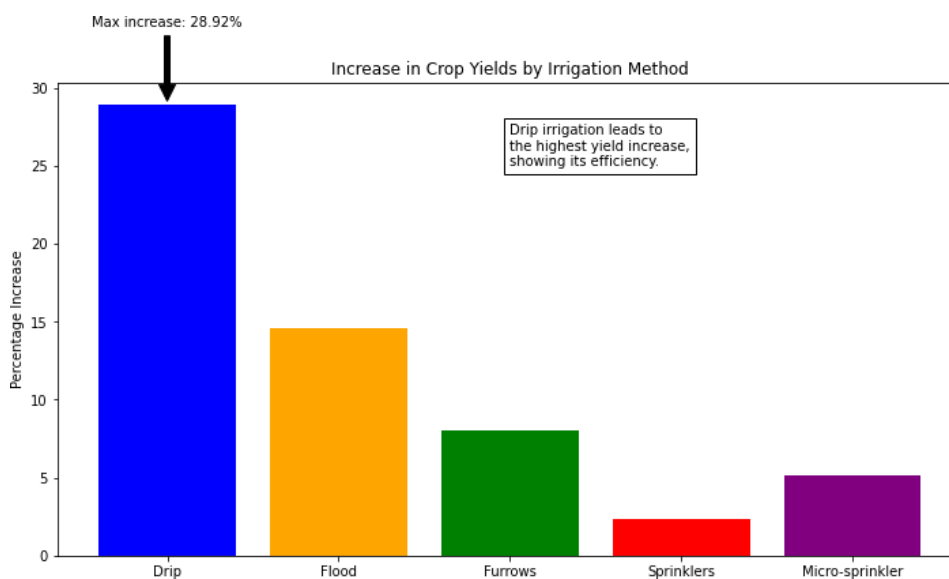


Fig 5. Increase in crop yield by using different irrigation methods

Crop modeling and precision agriculture

Precision agriculture and smart farming use innovative technologies to increase crop yield by precisely aligning resource inputs and anticipating crop types based on real-time data, weather patterns, soil conditions, and nutrient levels, supporting sustainable and efficient farming [65]. Crop-weed recognition and classification systems play a crucial role in precision agriculture, with the development of large-scale datasets and deep-learning models to accurately distinguish between crops and weeds in agricultural fields [66].

Future projections suggest an overall increase in runoff in the 10 typical basins due to rising precipitation throughout the 21st century. However, the potential impact of increased air temperatures may counteract precipitation effects in specific scenarios. It does not explicitly address altered precipitation patterns, temperature increases, extreme weather events, or regions experiencing reduced water availability due to various factor. Since 2000, primary river runoff in China has decreased in the east and increased in the west, notably in arid Northwest China. The

2000s–2010s saw a 34.7% average decrease in runoff at hydrological stations compared to the 1950s–2010s. Climate change and human activity contributed 53.5% and 46.5% to runoff changes in Chinese river basins, respectively. Global warming-induced precipitation and glacial meltwater have expanded the Qinghai-Tibet Plateau and Xinjiang lakes from 1995 to 2015. In terms of vulnerability, Northwest and North China exhibit high vulnerability, while the Northeast, East, South, and Central China show lower vulnerability. Southwest China varies, with Yunnan and Sichuan having lower vulnerability and Chongqing and Guizhou having higher vulnerability.

Southern China has seen increased water vulnerability since 2000, attributed to climate change and industrial and agricultural development, leading to heightened water resource exposure [67]. Climate change further exacerbates these challenges, leading to changes in precipitation patterns, rising temperatures, and an increased frequency of extreme weather events,

all impacting water availability for crop production. Efficient water management and water-saving techniques are essential for sustainable crop production and global food security. Countries worldwide are implementing various strategies to optimize water use in agriculture and mitigate the risks associated with water scarcity. Crop selection and breeding programs are being developed globally to enhance crop varieties with improved drought tolerance, water-use efficiency, and resilience to changing climatic conditions. Countries hope to reduce water use in agriculture while maintaining crop output by producing crop types that require less water and are better adapted to water-limited settings. Advanced irrigation technologies and management practices are also being adopted worldwide to maximize irrigation efficiency and minimize water losses. Techniques such as drip, precision, and deficit irrigation help deliver water directly to plant roots, reduce evaporation, and optimize water use based on crop water requirements. Furthermore, soil water conservation practices are crucial to global water-saving efforts. Conservation tillage, mulching, cover cropping, and soil moisture monitoring techniques help improve water retention in the soil, reduce runoff, and enhance overall water-use efficiency in agricultural systems.

Global water scarcity, which affects four billion people, is anticipated to rise due to population expansion, climate change, and rising food and energy demands. This imbalance between freshwater availability and demand affects blue water (from water bodies) and green water (soil moisture from rainfall). Agricultural green water scarcity occurs when rainfall is insufficient to meet crop needs. The study evaluates the detrimental effects of warming on rain-fed croplands, indicating that current conditions already imperil food production for 890 million people. Projections anticipate a rise to 1.23 and 1.45 billion people affected by 1.5°C and 3°C warming, respectively [68, 69].

In addition to on-farm practices, countries are exploring water recycling and reuse strategies to alleviate pressure on freshwater resources. Treating and reusing wastewater for irrigation purposes is gaining attention as a viable option to conserve water and reduce reliance on freshwater sources. The global scenario emphasizes the urgency of adopting efficient water-saving techniques in agriculture to address water scarcity and ensure sustainable crop production.

Collaboration between researchers, policymakers, and farmers is crucial to sharing knowledge, implementing best practices, and developing innovative solutions tailored to specific regional needs and climatic conditions. The introduction gives an overview of the global problems with water scarcity and stresses the need for efficient water-saving practices in farming. It emphasizes the need for a concerted global effort to optimize water use, enhance water productivity, and ensure food security in the face of changing climatic conditions and increasing demands for agricultural products. Water scarcity and its impact on agriculture are particularly significant in China due to its vast agricultural sector and diverse climatic conditions. China faces multiple challenges, including increasing water demand, declining water resources, and uneven water distribution across different regions.

With more than 1.4 billion people living there, China's agriculture industry significantly guarantees food security. However, little water is available for irrigation, particularly in arid and semi-arid areas. Furthermore, by changing precipitation patterns, increasing the frequency of extreme weather events, and escalating water scarcity, climate change exacerbates these problems. China has realized the need to implement effective water-saving agricultural techniques to address these problems. The country has implemented various initiatives and programs to promote sustainable water management practices. These efforts aim to optimize water use, improve water productivity, and ensure the long-term viability of crop production. Based on estimations from the Difference-in-Difference (DID) empirical technique, grain production in the Yellow River Basin has improved dramatically since China's National Agricultural Water-Saving Outline was implemented in 2012 [70]. The agricultural water-saving policy has effectively supported several input elements in grain production by assuring water demand. Consequently, this has increased water production in farming operations, guaranteeing effective water use.

In China, efficient water-saving techniques encompass a range of approaches tailored to local conditions. These may include specific crop selection and breeding programs that focus on developing varieties with enhanced drought tolerance, water-use efficiency, and adaptability to varying agro-climatic zones within the country. Furthermore, advanced irrigation technologies and

management strategies are implemented in Chinese agriculture. Drip irrigation systems, precision irrigation methods, and improved water delivery systems are being adopted to minimize water losses, increase irrigation efficiency, and reduce water consumption in crop production. Soil water conservation practices are also receiving attention. These practices involve using conservation tillage techniques, mulching, cover cropping, and soil moisture monitoring to enhance water retention in the soil, reduce evaporation, and improve overall water-use efficiency. Additionally, the country is exploring the potential for water recycling and reuse in agriculture. Wastewater treatment technologies and safe irrigation practices are being developed and implemented to utilize treated wastewater for irrigation purposes, conserve freshwater resources, and reduce pollution. The challenges and initiatives related to China's crop production and water conservation emphasize the importance of efficient water-saving techniques tailored to China's unique agricultural landscape and climatic conditions. By implementing these techniques, China aims to enhance water productivity, mitigate water scarcity risks, and ensure sustainable crop production to meet the needs of its growing population.

Water scarcity and climate change are significant challenges threatening global food security, particularly in regions heavily reliant on agriculture. Among the largest countries, it faces unique challenges in ensuring sustainable crop production while managing limited water resources. Cropland regions and China's food security are under threat by rising temperatures. China's farmland area is expected to decrease by 2.09%–25.51% due to climate change [71]. As climatic conditions change, exacerbating water scarcity, adopting efficient water-saving techniques in agriculture becomes crucial for sustaining crop production. China is one of the countries where the concern over how climate change would affect water resources is the greatest worldwide. Increased temperatures, more extreme weather events, and changed precipitation patterns are ways climate change is exhibiting itself. These changes have far-reaching effects on the distribution and availability of water resources in various places, which presents a great deal of difficulty for agricultural practices. Research indicates that certain regions in China are grappling with reduced water availability due to declining precipitation and the retreat of glaciers in high-altitude areas. Furthermore, shifts in

precipitation patterns, marked by intensified rainfall but reduced frequency, can contribute to heightened runoff and diminished water infiltration in agricultural soils, compounding the challenges of water scarcity.

GIS and remote sensing in irrigation water management emphasize their potential for enhancing water usage efficiency. While highlighting technological advancements, it falls short of explicitly addressing the transition from traditional irrigation practices or the importance of precision agriculture technologies. The study underscores the current and future applications of GIS and RS in sustainable irrigation water management [72].

Efficient water management practices are pivotal in agriculture, particularly in China, where conventional methods like flood irrigation led to significant water losses. Transitioning to sustainable techniques such as mulching, drip irrigation, and precision agriculture using GIS and remote sensing is crucial to optimizing crop yield and conserving water resources. Drip irrigation, with its targeted water delivery directly to the plant root zone, is a practical water-saving approach. It promotes enhanced water use efficiency, reduced evaporation and runoff, and improved crop yield. Various drip irrigation layouts offer unique advantages, contributing to minimized nutrient leaching and increased water and fertilizer use efficiency.

Despite the benefits of water-saving techniques like drip irrigation and sprinkler irrigation in China, challenges persist, including high initial costs, maintenance needs, and the risk of clogging. Sprinkler irrigation, widely adopted, mimics natural rainfall over crops, providing advantages like reduced water consumption and improved irrigation uniformity. However, addressing issues such as increased energy requirements, potential evaporation losses, and reduced efficiency in windy conditions is essential for optimal implementation.

Subsurface irrigation, an innovative water-saving method, directs water directly to plant roots through concealed lines or mechanisms, minimizing losses from evaporation and surface runoff. Tailored to crop needs and soil properties, this approach employs perforated or porous pipes beneath the soil surface for precise water delivery. Advantages encompass decreased water usage, control of weed growth, better nutrient management, and promoted root development. Nevertheless, potential challenges, such as root

zone salinization and elevated installation costs, need careful consideration for successful implementation.

In the realm of subsurface irrigation, the advantages are manifold. This technique delivers water with precision directly to the roots, minimizing losses from evaporation and runoff. Furthermore, it optimizes water uptake, reducing wastage and ensuring an efficient and targeted hydration process for plant roots. The controlled moisture distribution associated with subsurface irrigation not only limits weed growth by restricting moisture availability for weeds but also integrates seamlessly with fertigation systems, facilitating the precise application of nutrients to the root zone. As a result, this approach fosters the development of healthier plants with robust root systems.

The cost of materials and installation makes the initial investment in subsurface irrigation systems costlier. A possible risk of salt accumulation exists in areas with elevated soil salinity if appropriate management methods are not implemented. Its ability to adjust to shifting crop growth patterns and water requirements may mean routine cleaning, inspection, and maintenance to keep things clear and guarantee even water distribution. It is necessary to adjust the system design to particular site variables, such as crop variety, soil type, and local circumstances, to achieve optimal performance.

Shifting the focus to mulching, this practice encompasses various types, each offering distinct benefits. Organic mulch, including materials like straw, compost, wood chips, and leaves, assists in preserving soil moisture by diminishing water evaporation and decreasing the necessity for frequent irrigation. It also acts as a physical barrier, suppressing weed growth and minimizing crop competition. Inorganic mulch, including plastic films, geotextiles, and gravel, provides additional benefits such as temperature moderation and erosion control. Living mulch, achieved through cover crops or intercropping, contributes to ground cover, further enhancing weed suppression and fostering soil fertility.

Nonetheless, there are difficulties in the field of mulching. Costs related to material procurement and application may be factors to consider. Certain forms of mulch, particularly organic materials, might foster pest and disease growth, needing close monitoring and treatment. Organic mulch may temporarily bind up nutrients during decomposition, potentially necessitating extra

fertilizer applications. Periodic inspection and mulch replacement ensure efficacy and prevent difficulties such as weed growth and water intrusion. Developing a biodegradable and biocompatible ethyl-cellulose radiative cooling mulch results in a remarkable 60% reduction in soil moisture loss and a corresponding 30% increase in plant growth [73]. The utilization of rice husk mulch demonstrated a notable enhancement in germination percentage, yield, and economic returns for pea cultivation. Specifically, employing rice husk mulch at 60 quintals per hectare yielded the highest germination percentage and grain yield [74]. Mulch size and quality affect soil microbiology, nutrient dynamics, and decomposition rate. Long-lasting mulches maintain soil fertility without negatively affecting crop productivity [75].

Conventional methods of agriculture can be improved if there is certainty about the availability of water supplies. It may be possible to find a solution to the issue of managing the application of irrigation water during drought by regulating the quantity and timing of irrigation at various phases of crop growth. Agricultural water use efficiency (WUE) can be greatly improved with the help of crop models [76]. These models provided dynamic information on soil water and crop growth, which was required for efficient irrigation scheduling, was provided by these models. These elements include crop growth, soil water movement, and environmental conditions [77]. Crop models can account for the availability and cost of water resources to calculate the plant water deficit index (PWDI) threshold corresponding to distinct combinations of yield and WUE. On-demand watering, which decreases water waste and enhances WUE, is just one example of an irrigation method that may be analyzed using a crop model to determine its effect on WUE.

Additionally, crop models can be utilized in the following contexts: evapotranspiration modeling, model construction, and parameterization, coordinated water and nutrient management, soil water management, risk assessment of water-limited irrigation management, and regional assessments of climate effects. Overall, crop models contribute to sustainable, water-efficient management by providing significant insights and suggestions for managing water use in agriculture. The threat to agricultural sustainability in the North China Plain (NCP) is driven by insufficient irrigation practices, leading to the loss of groundwater and the adverse effects of climate

change [78]. Modern water-saving cultivation techniques have been devised by researchers utilizing crop models, which significantly reduce irrigation volumes and reduce carbon footprints without losing grain yields [79].

Sustainable irrigation methods, like a winter wheat/summer maize/single maize rotation system that can reduce groundwater depletion, are identified with the help of crop models [80]. Using crop models will lead to more environmentally friendly irrigation methods and sustainable farming in China. Numerical crop models replicate plant, weather, soil, and management practice interactions to assist farmers in better understanding and quantifying the trade-offs between yield, care, and long-term viability. They have been adopted on various scales, from local farms to regional and global levels, to assess the effects of climate change, optimize crop combinations, and progress sustainable agriculture. These models' parameters can be adjusted to simulate various crops' growth, development, and yield. Crop models, on the other hand, have several limitations, such as a lack of sensitivity to some environmental circumstances and a static view of nutrient dynamics. Despite these caveats, crop models help learn about and develop new cropping systems, and they can be easily validated using data from the literature and in-field studies [81, 82].

Various agricultural practices offer unique advantages, yet they pose challenges and require careful consideration for successful implementation. Adopting sustainable agricultural practices, including organic farming, agroforestry, precision agriculture, and enhanced water management strategies, is crucial for increasing food demands while mitigating adverse effects [83]. Nonetheless, farmers may need help applying sustainable land management practices, which can be attributed to factors such as insufficient education and neglect by government

officials.

The incorporation of sensor-based irrigation management represents a pioneering approach in modern agriculture. This study is centered around an Internet of Things (IoT)-based intelligent irrigation system, utilizing sensors and IoT technology to enable real-time monitoring and control of various irrigation parameters [84].

The discourse on employing soil moisture sensors for irrigation decisions in mountain terrace agriculture overlooks specific considerations such as optimizing water application and leveraging real-time data for efficient irrigation scheduling [85]. Additionally, although the fabrication of affordable and flexible soil moisture sensors with interdigitated electrodes is thoroughly explained, there remains a need for further insights into the optimization of water application across agricultural fields and effective irrigation scheduling practices [86].

Weather sensors are instrumental in continuously monitoring environmental factors like temperature, humidity, and air quality. This real-time monitoring empowers farmers to make precise irrigation decisions, considering the current meteorological conditions [87]. Agricultural innovations and the effects of climate change on agriculture. It covers important topics such as crop modeling, precision agriculture, the impact of climate change on agriculture, water management techniques, crop and soil management practices, and technological advancements. Each category is quantified by a percentage, demonstrating the progress or effects within that specific domain. This visual summary succinctly depicts the fundamental aspects of the extensive data provided, emphasizing the advancements and difficulties in sustainable agriculture and water management as of 2023. Agricultural Innovations and climate impact is shown in Fig 6.

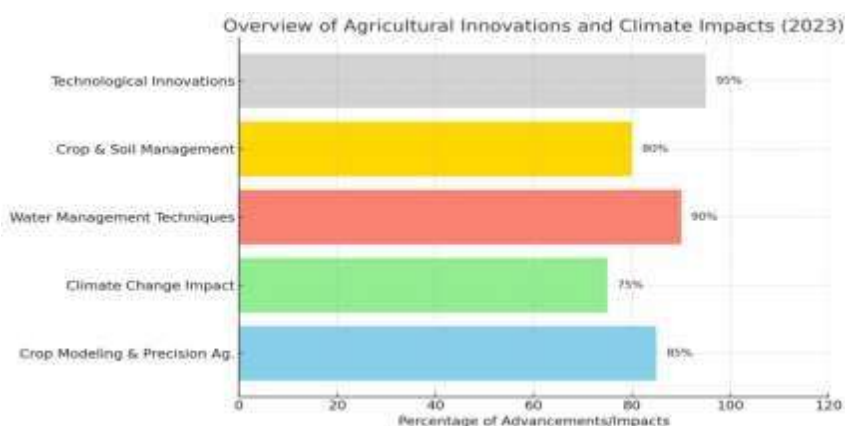


Fig 6. Agricultural Innovations and climate impact

Plant-Based Sensors:

The system's precision is further enhanced by plant-based sensors, which delve into crop physiology, providing insights into water needs and stress levels. Integrating sensor technologies significantly improves water use efficiency, minimizing waste and optimizing overall use. Fine-tuning irrigation practices based on real-time data enhances crop yield and quality, advancing agricultural productivity.

Precision agriculture ensures resource conservation, applying water and inputs where and when needed. Timely decision-making, facilitated by real-time sensors and remote sensing data, empowers prompt actions in irrigation, fertilization, and agronomic practices. The adaptability of precision agriculture to field variability allows for site-specific management, offering customized approaches tailored to different areas within a field. However, notable challenges include the upfront investment for technologies requiring equipment, sensors, and data management systems. Technical expertise and adept data interpretation are prerequisites for successful implementation. Regular maintenance and calibration are crucial for data accuracy and reliability. Effective utilization of precision agriculture technologies depends on robust data management, analysis, and seamless integration with decision support systems. Economic feasibility necessitates careful evaluation based on crop, farm size, and local conditions, considering the overall cost-benefit ratio. In essence, farmers navigating the path of innovation must weigh considerable advantages against demands and limitations to determine the actual value of sensor-based irrigation management in their agricultural practices.

Importance of Water Resources in Agriculture: Addressing Climate Change Challenges in China

Water is an indispensable resource for agriculture, serving as the lifeblood of farming systems around the globe. In China, where agriculture plays a critical role in feeding the world's largest population, the importance of water resources cannot be overstated. The interplay between water availability and agricultural productivity is a delicate balance, now increasingly threatened by climate change [88].

Climate change poses multifaceted challenges to water resources, significantly impacting agricultural practices in China. Altered precipitation patterns, characterized by the

increased frequency of extreme weather events such as droughts and floods, directly affect the availability of water for crop production. These alterations lead to more frequent droughts in some areas, while others may experience reduced rainfall or more intense rainfall events, resulting in runoff and soil erosion [89]. Such changes not only disrupt traditional farming practices but also highlight the urgent need to adopt water-saving techniques to combat the resultant water scarcity [90].

Rising temperatures further exacerbate the situation by increasing evapotranspiration rates, thereby elevating the water demands of crops [91]. This scenario intensifies the necessity for efficient water management practices aimed at optimizing water use and ensuring crops receive adequate water without excessive losses [92]. Additionally, shifts in hydrological cycles, including changes in the timing and distribution of water resources, such as river flows and groundwater recharge patterns, necessitate adjustments in agricultural practices to align with the new water availability realities [93-95].

The impact of these climate-induced challenges on agricultural productivity and food security in China is profound. As climate change continues to influence water availability, it becomes critical to adapt agricultural methods to ensure sustainable crop production. Advanced irrigation methods like drip and precision irrigation have emerged as key solutions, demonstrating their effectiveness in maximizing water use and minimizing losses [96]. Similarly, crop selection and breeding programs that focus on enhancing drought tolerance and water-use efficiency are crucial for improving crop performance under limited water availability [97, 98].

The adoption of soil water conservation practices, such as conservation tillage and mulching, further supports water retention in the soil and optimizes water-use efficiency, thereby enhancing the resilience of agricultural systems to water scarcity induced by climate change [99]. The challenges posed by climate change to water resources in China underscore the critical importance of water in agriculture. By implementing adaptive measures and embracing innovative water management and conservation techniques, China can protect its agricultural production, ensure food security, and maintain the resilience of its agricultural system against the backdrop of a changing climate [100, 101].

Water-Saving Techniques

A. Crop Selection and Breeding:

Crop selection and breeding are pivotal in developing drought-tolerant, water-efficient varieties. Ongoing research focuses on identifying genetic traits for enhanced water-use efficiency [102, 103]. Molecular techniques, including marker-assisted selection and genetic engineering, expedite the development of drought-tolerant crops [104, 105].

B. Irrigation Management:

Various techniques and strategies optimize water use [106]. Drip irrigation minimizes losses through evaporation and runoff [107, 108]. Precision irrigation technologies, such as soil moisture sensors, enhance efficiency [109, 110]. Deficit irrigation promotes water-use efficiency without significant yield compromise [111].

C. Soil Water Conservation:

Practices like no-till, mulching, and cover cropping enhance water retention. Soil moisture sensors and remote sensing technologies provide real-time information [112, 113].

D. Water Recycling and Reuse:

Treating and reusing wastewater for crop irrigation is a promising practice. Proper treatment methods are necessary to remove contaminants [114, 115]. Challenges include health risks and the need for monitoring and regulatory frameworks [116].

Adoption and Barriers:

Economic considerations, farmer knowledge, and policy support influence adoption [117]. Limited access to finance, awareness, and technical knowledge pose barriers [118]. Institutional and policy challenges, climate variability, and water data limitations complicate adoption [119, 120].

Addressing Barriers and Promoting Adoption:

A comprehensive strategy involves farmer education, access to finance, supportive policies, and community engagement. Technological barriers require affordable and accessible solutions. Scalability and adaptability are crucial and tailored to diverse conditions. Collaboration among stakeholders, incentives, and support systems facilitate adoption [121-123].

Holistic Approach:

Factors like social and behavioral influences, institutional support, and access to water resources impact adoption. Peer-to-peer learning,

demonstrations, and success stories foster positive attitudes [124, 125]. Government coordination, regulations, and infrastructure support ensure a favorable environment [125].

Influence of Socio-Economic Factors on Adoption:

Adopting water-saving techniques is intricately linked to the socio-economic context and specific farm characteristics. Variables such as farm size, land tenure systems, labor availability, and economic conditions shape the feasibility and practicality of water-saving techniques [126, 127]. Recognizing and tailoring interventions to accommodate diverse needs and capacities within different farming systems and socio-economic contexts is pivotal for fostering successful adoption [128].

In summary, understanding the complexities of adopting water-saving techniques in agriculture requires a comprehensive examination of various factors, including social dynamics, institutional frameworks, governance, and infrastructure. Practical strategies to promote adoption must encompass approaches that bridge knowledge gaps, account for social dynamics, address policy frameworks, and ensure equitable access to resources. The extensive and successful adoption of water-saving techniques hinges on fostering stakeholder collaboration, encouraging participatory decision-making, and customizing interventions to meet farmers' and farming systems' specific needs and contexts.

Effective Implementation of Water-Saving Techniques:

Numerous case studies exemplify the successful application of water-saving strategies in Chinese agricultural production, showcasing their effectiveness in addressing water scarcity and promoting sustainability. Real-world examples emphasize how efficient irrigation practices can effectively combat water scarcity. Key instances include:

Case Study 1: implemented drip irrigation systems in a wheat field in Hebei Province, reporting substantial reductions in water consumption and higher crop yields compared to traditional flood irrigation. The success of drip irrigation showcased its effectiveness in conserving water resources and improving crop productivity [129].

Case Study 2: explored subsurface irrigation in rice cultivation in Zhejiang Province, revealing reduced water usage, improved crop growth, and higher grain yields compared to conventional flood irrigation. The successful implementation underscored the potential of subsurface irrigation for water conservation and enhancing rice production [130].

Case Study 3: examined sprinkler irrigation systems adoption in Shandong Province's vegetable production, reporting reduced water consumption, enhanced irrigation uniformity, improved crop quality, and higher marketable yields. The successful implementation of sprinkler irrigation demonstrated its effectiveness in optimizing water use and enhancing crop outcomes [131].

Comparative Studies on Water-Saving Techniques:

Comparative studies assessing different water-saving techniques have been conducted to gauge their performance and identify the most effective options for specific crops and regions. These studies offer valuable insights into various water-saving methods' relative merits and limitations. Key findings include:

Study 1: In a comparative study of irrigation methods for maize cultivation in Henan Province, four micro- sprinkler techniques were examined against traditional practices like drip and sprinkler irrigation [132]. The study found that the W4 method, which irrigates at 60% of the field's water-holding capacity, was notably superior. It enhanced crop yields by 20% and reduced water loss by 39.4%, demonstrating a significant advancement over conventional irrigation methods.

Study 2: Dwarf Fuji apple orchards were studied from 2017 to 2022 to determine optimal irrigation and nitrogen levels. Findings revealed that 85% of field capacity irrigation with 240 kg/ha nitrogen maximized apple yield and quality while enhancing soil health [133].

These comparative studies provide valuable insights into the performance and suitability of different water-saving techniques in specific agricultural systems, offering farmers, policymakers, and researchers guidance in selecting appropriate irrigation methods based on crop requirements, water availability, and local conditions.

Effect of Water-Saving Techniques on Crop Yield and Quality:

Various studies have explored the repercussions of water-saving techniques on crop yield and quality in China, scrutinizing how efficient irrigation practices impact plant growth, yield components, and crop attributes. Key findings encompass:

Study 1:

Scrutinized the influence of drip irrigation on maize yield and quality in Gansu Province. The study disclosed that drip irrigation significantly augmented maize yield, ear weight, and kernel weight compared to flood irrigation. Additionally, drip-irrigated maize displayed enhanced starch content and reduced moisture levels, indicating superior grain quality [134].

Study 2:

The impact of sprinkler irrigation on tomato yield and quality in the Xinjiang Uygur Autonomous Region. The findings revealed that sprinkler irrigation heightened tomato yield, fruit size, and soluble solids content compared to flood irrigation. Furthermore, sprinkler-irrigated tomatoes exhibited improved color, firmness, and vitamin C content, signifying enhanced fruit quality. These studies underscore the affirmative influence of water-saving techniques on crop yield and quality across diverse agricultural systems in China, emphasizing the potential of efficient irrigation practices to augment productivity, optimize resource utilization, and elevate the marketability of agricultural produce.

Economic Viability of Water-Saving Techniques:

The economic feasibility of water-saving techniques constitutes a pivotal aspect of their widespread adoption in agriculture. Various studies have assessed the economic viability and return on investment linked with implementing efficient irrigation practices. Key insights include:

Study 1: An economic analysis of drip irrigation systems for cotton production in Xinjiang Province, demonstrating that despite higher initial investment costs, drip irrigation yielded significantly higher net returns than flood irrigation, attributed to improved water use efficiency and increased cotton yield [135].

Study 2: The economic viability of subsurface irrigation in rice cultivation in Anhui Province. The study found that while subsurface irrigation incurred higher installation costs, the augmented

rice yield and water savings translated into superior economic returns and enhanced profitability compared to conventional flood irrigation [136].

These economic evaluations spotlight the enduring benefits and potential profitability of water-saving techniques for farmers, contributing to a nuanced understanding of the economic feasibility and sustainability of adopting efficient irrigation practices in Chinese agriculture.

Policy and Institutional Framework:

Government Initiatives and Programs:

The Chinese government has instituted robust policies and programs fostering water-saving practices in agriculture to combat escalating water scarcity and climate change impacts. Key initiatives include approving a national-territorial spatial plan for Yunnan province, prioritizing ecological protection and maintaining a minimum cultivated area. A significant commitment is evident through an investment exceeding 1 trillion yuan in major water conservancy projects, underscoring the dedication to bolstering water infrastructure. Notably, China has attained global average water-use efficiency and achieved 83% rural tap-water coverage, marking substantial strides in providing clean water access. The extensive coverage of 37.8 million hectares in water-saving irrigation attests to China's commitment to sustainable agriculture, addressing challenges posed by water scarcity.

Overview of Crop Models:

In agricultural research, crop models like APSIM and DSSAT have significantly advanced, offering accurate crop growth and yield predictions under diverse conditions. These models excel in assessing various agricultural outputs rapidly and reliably. AquaCrop is specialized in evaluating water usage in rainfed and irrigated systems, while its capabilities in nitrogen dynamics assessment are less robust than others. JULES addresses food security vulnerability by integrating agricultural and socio-economic factors. ORYZA, designed for paddy rice, highlights the importance of crop-specific models. APSIM, DAISY, and DSSAT are frequently used for grain filling analysis, a critical crop development phase. These models also aid in decision-making for water conservation and have improved farming practices, including planting and irrigation planning. They're instrumental in adapting agriculture to climate change, integrating technologies like deep learning for disease detection and resource conservation. Despite their

utility, limitations exist, such as challenges in obtaining reliable input data and capturing all process details affecting crop growth.

The Use of Crop Models to Enhance Water Efficiency in China:

In China, the strategic application of crop models has significantly advanced water efficiency in agriculture. Comprehensive studies across diverse regions have utilized these models to assess various irrigation methods, scrutinize crop growth patterns, and evaluate water utilization efficiency. These investigations have provided deep insights into optimizing irrigation for enhanced food yield and underscored the transformative impact of crop models in sustainable agricultural practices. The results from these studies have been instrumental in shaping policies and farming techniques that prioritize water conservation while maintaining or even increasing agricultural productivity, as evidenced by several key studies:

- 1. Liu et al. (2023):** Developed a water-saving system that reduced irrigation needs while increasing grain yield, surpassing traditional methods.
- 2. Yang et al. (2023):** Drip irrigation is superior to other water-saving methods and enhances crop yields, based on a comprehensive meta-analysis.
- 3. Wang et al. (2023):** Analyzed crop water use in multiple cities, proposing strategies to balance regional water consumption.
- 4. Kandasamy et al. (2023):** Enhanced soil temperature predictions by integrating multiple simulation models.
- 5. Yin et al. (2023):** Reported inconsistencies in simulating sugarcane production using global models.

These findings highlight the versatility of crop models in agriculture, from fine-tuning irrigation plans to improving agronomic practices and addressing soil-plant-atmosphere interactions. They have been instrumental in managing water stress in crops, supporting irrigation decision-making, and optimizing resource use. By integrating varied data for real-time simulations, these models have significantly bolstered water management in agriculture. This progress not only boosts water productivity but also aids in developing inter-sectoral water management policies, underscoring the vital role of crop simulation models in addressing China's agricultural water challenges.

Advancements and Challenges in Crop Modeling for Water-Saving Developments in Crop Modeling

Micro-irrigation and Sprinkler Irrigation:

Revolutionizing crop production, these water-saving methods have drastically cut water requirements, steering agriculture towards greater efficiency in water usage [137]. **Dynamic Crop Simulation Models and DSS:** Playing a pivotal role in irrigation optimization, these models delve into the intricate dynamics between plant growth, soil moisture, and water stress, significantly boosting agricultural water use efficiency [138].

Remote Sensing Technologies: The adoption of satellite imagery and drones has transformed agricultural practices, providing vital information on water needs, soil moisture, and crop health, thus significantly refining the accuracy of crop models [139].

Artificial Intelligence (AI): AI's integration into the agricultural sector has been transformative, enhancing everything from pest management to soil monitoring and utilizing data to improve crop production and water management [140].

Development of the SIMPLE Model: Designed for broad adaptability, the SIMPLE model caters to diverse crops, requiring data on daily weather, management practices, and soil properties to function, serving as a versatile tool in crop modelling [141].

Challenges and Limitations

Model-specific Uncertainty: Predictive reliability is often hampered by inherent model uncertainties, which can undermine the effectiveness of their outputs [142].

Data Quality and Availability: Gathering comprehensive, high-quality data for model calibration and validation remains a formidable challenge. It underscores the need for a multifaceted strategy that merges remote sensing, field experiments, secondary data, and farmer collaboration [143].

Influence of Socioeconomic Factors: The adoption of sustainable agricultural practices is significantly influenced by socioeconomic factors such as household income, education level, and access to training on water-saving technologies [144].

In conclusion, despite the promising strides in crop modelling towards enhancing water conservation in agriculture, the sector faces ongoing challenges. Overcoming the hurdles of model uncertainty, improving data quality, incorporating cutting-edge technologies, and acknowledging socioeconomic impacts are

crucial. These advancements and challenges highlight the evolving nature of crop modelling in its quest for sustainable and efficient water use in agriculture.

Case Studies in Crop Modeling for Water-Saving

- 1. AquaCrop Model for Maize:** The AquaCrop model outperformed CERES-Maize in simulating maize yield under varied irrigation and nitrogen levels, with grain yield simulation errors of 8% for AquaCrop and 5% for CERES-Maize [145].
- 2. APSIM-Wheat and AquaCrop for Wheat:** Calibration and Validation of AQUACROP and APSIM Models to Optimize Wheat Yield and Water Saving in Arid Regions" discovered that, in the case of applying 120% of the recommended nitrogen and 0.8 times actual evapotranspiration, the highest wheat yield ranged from 6.8 to 8.7 tons per hectare, with water productivity (WP) reaching up to 2.0 kg/m³ [146].
- 3. AquaCrop for Wheat and Maize in North China Plain (NCP):** Assessment of the AquaCrop Model under different irrigation scenarios in the North China Plain" found that winter wheat had a Normalized Root Mean Square Error (NRMSE) for grain yield between 2.00-9.90% under full irrigation and summer maize 5.95%. Winter wheat had a 5.80-16.00% NRMSE for grain yield under water-saving irrigation, while summer maize had 9.51%. The AquaCrop model simulates grain yield and biomass accurately under full irrigation but less accurately for winter wheat under water-saving irrigation [78].
- 4. APSIM for Agricultural Systems:** APSIM-Wheat yield predictions are most sensitive to initial nitrogen content, soil parameters, and precipitation. Sensitivity varies with environmental and management conditions, emphasizing the importance of optimizing nitrogen application and water availability for accurate yield forecasting [147].
- 5. DSSAT for Groundwater Management:** Machine learning models for estimating evapotranspiration (ET_o) and their impact on irrigation water use in sweet corn via DSSAT. It finds Neural Network and Random Forest models outperform empirical ones, with incorrect ET_o model choices potentially leading to over-irrigation by up to 54 mm per crop season [148].
- 6. CropSyst for Winter Wheat and Summer Maize:** The CropSyst model simulates

evapotranspiration, biomass, and yield for winter wheat and summer maize on the North China Plain, showing that 30-40% of water use is evaporation. It emphasizes efficient irrigation to reduce water loss and improve crop water use [149].

7. **AquaCrop, CropSyst, and WOFOST for Sunflower:** AquaCrop, CropSyst, and WOFOST were compared for Mediterranean sunflower growth simulation under different water regimes. Using a water-driven approach, AquaCrop simulated biomass and yield, as well as CropSyst and WOFOST, suggesting simpler models can work with limited data [150].
8. **WOFOST for Winter Wheat in China:** Combining MODIS LAI data with TIGGE weather forecasts and historical data improved winter wheat yield predictions in Hebei, China, between 2009 and 2013. The model's spatial variability calibration suggests regional crop yield forecasting potential [151].
9. **DSSAT and APSIM for Rice-Wheat Systems:** Adaptation strategies in Pakistan's rice-wheat agricultural system showed potential for mitigating climate change impacts, with modelling indicating improved outcomes through strategies like increased sowing density and advanced fertilization methods. Despite climate challenges, these adaptations could bolster resilience and livelihoods in affected farming communities [152].
10. **SAMARA for High-Yield Rice Cultivars:** The study on 12 rice genotypes shows that high and low tillering types adapt to varying conditions, ensuring stable yields. Traits like tiller production and panicle size influence yield potential under different conditions. The SAMARA model accurately predicts these adaptations, which is valuable for designing adaptable rice ideotypes [153].

Findings:

This study underscores the critical role of advanced irrigation techniques—such as drip, precision, and deficit irrigation—in significantly improving water use efficiency within agricultural systems. These methods, by targeting water directly to the plant's root zone, provide effective solutions to the urgent need for water conservation. The research further emphasizes the importance of developing drought-resistant and water-efficient crop varieties as a fundamental strategy to maintain crop yields under conditions of water scarcity. It also identifies the significant

potential of water recycling and reuse, facilitated by modern treatment technologies, as vital for maximizing the utilization of water resources and alleviating the impacts of water scarcity. A collaborative approach involving researchers, policymakers, and the agricultural community is highlighted as essential for advancing these water-saving practices. The necessity for continuous innovation and robust policy support is emphasized to ensure the successful implementation of these strategies. Tailoring these techniques to suit China's unique climatic conditions is crucial for enhancing the resilience of the agricultural sector, thereby safeguarding China's food security and promoting sustainable agricultural development in the face of increasing water constraints and climate change.

Future Perspectives:

The evolution of agricultural water management in China is poised to leverage cutting-edge technologies and foster the development of climate-resilient crops. The integration of artificial intelligence, remote sensing, and the Internet of Things (IoT) into smart irrigation systems, coupled with genetic advancements in drought-resistant crops, is expected to play a pivotal role. These technological interventions will be crucial in optimizing water use efficiency and adapting to variable climatic conditions. Additionally, robust interdisciplinary research and comprehensive policy frameworks will be vital to ensure sustainable water allocation and effective implementation of water-saving innovations. Strengthening collaboration among scientists, policymakers, and the agricultural community is essential to address the multifaceted challenges posed by climate change and water scarcity. By fostering these synergies, China aims to develop a resilient agricultural sector capable of supporting its growing population in an era of increasing environmental constraints.

Gaps or Shortcomings:

Our review has illuminated several significant gaps that warrant further attention to enhance the efficacy of water-saving practices in agriculture. Primarily, there exists a notable deficiency in comprehensive comparative research that spans diverse regions, crop types, and climate conditions. This limitation restricts our understanding of the broader applicability and potential of drip irrigation and other water conservation methods across varying agricultural contexts. Moreover, the long-term effects of these practices on biodiversity, groundwater levels, and

soil health are often overlooked in existing studies, posing a significant gap in our assessment of their sustainability.

Additionally, there is a scarcity of research focused on the economic viability of water-saving techniques for smallholder farmers. This includes a lack of detailed analysis of the policy frameworks and educational programs necessary to facilitate their adoption. The variability in adoption rates across different regions further underscores the need for research that incorporates socioeconomic, cultural, and environmental factors to understand and address regional disparities.

Furthermore, research on the integration of water-saving practices with other sustainable agricultural methods remains limited. Addressing these gaps is crucial for developing a holistic approach to sustainable agriculture.

Our comprehensive review aims to bridge these knowledge gaps, providing a foundational guide for future research and policy-making. By fostering a deeper understanding and promoting the broader adoption of these practices, we can better integrate them into sustainable agricultural frameworks globally.

Recommendations:

To effectively address water scarcity and bolster agricultural sustainability, several strategic initiatives are recommended for implementation across China:

1. Adoption of Precision Agriculture:

- It is crucial to adopt precision agriculture techniques that enhance water use efficiency. These practices include advanced irrigation systems that deliver water directly to the plant roots, thereby reducing waste.

2. Soil Moisture Conservation Techniques:

- Promoting soil moisture conservation methods, such as mulching and conservation tillage, should be prioritized. These techniques help retain soil moisture, reduce evaporation, and improve soil health, contributing to water conservation.

3. Investment in Water Recycling and Reuse:

- Investing in infrastructure for water recycling and reuse is essential. Such systems ensure that water resources are utilized more efficiently and can significantly reduce the dependence on freshwater supplies.

4. Strengthening Water Governance:

- Stronger water governance mechanisms are necessary to manage water resources effectively. This includes the implementation of policies that support sustainable water use

and the enforcement of regulations that protect water resources.

5. Public Awareness and Education:

- Raising public awareness about the importance of water conservation is fundamental. Educational programs should be developed to inform citizens and farmers about the benefits of water-saving practices and encourage their adoption.

6. Monitoring and Evaluation:

- Implementing mechanisms to monitor the effectiveness of water-saving initiatives is vital. These systems should track progress, evaluate the impact of implemented practices, and inform policy adjustments to enhance their effectiveness.

7. Coordinated Policy Support:

- A coordinated approach involving policy support, educational initiatives, and technological innovation is necessary to drive the adoption of sustainable practices. This integrated effort will help secure China's agricultural productivity and sustainability in the face of ongoing climate challenges.

By implementing these recommendations, China can significantly advance its agricultural sustainability, effectively manage water resources, and enhance resilience to climate change impacts.

Conclusion:

In conclusion, this review emphasizes the critical importance of implementing water-saving techniques in China's agricultural sector to concurrently secure food security and manage water resources sustainably amid evolving climate change pressures. By meticulously analyzing diverse strategies, including advanced irrigation methods, selective crop breeding for drought resistance, and enhanced soil water conservation practices, the review illuminates the substantial potential to boost water use efficiency across agricultural systems.

Moreover, the paper stresses the vital role of collaborative endeavors among scientists, policymakers, and the agricultural community in promoting the adoption and successful implementation of these water-saving strategies. It calls for continued research and technological innovation, coupled with robust policy support, to adeptly navigate the intricacies of water management within the agricultural context.

By adopting these water-saving techniques tailored to China's distinct climatic and hydrological conditions, the review projects that the country can substantially improve its

agricultural productivity, effectively conserve its limited water resources, and ensure a sustainable food supply for the future. This integrative approach not only holds profound implications for China but also provides valuable insights and adaptable models for other regions grappling with similar challenges of water scarcity and climate change.

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