Agriculture and Water Management: Strategies for Precision On-Farm Water Management

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Abstract

Water is a foundational component of supporting ecosystems, the climate, and all living organisms. Fresh water drives all global systems, but most specifically agriculture and livestock. Agricultural industries' consumption of water accounts for 70% of all water that is consumed annually. Of the 2 quadrillion gallons of water that are used, upwards of 40% is lost due to water inefficiency and waste. Such losses contribute to rises in poverty levels, food insecurity, GDP declines by as much as 6%, and water shortages. With the global population expected to reach almost 10 billion by 2050, there is a clear need to optimize agricultural production by enhancing water use efficiency. These alarming statistics emphasize the need to transition to more sustainable water management systems. The objective of this review is to identify and evaluate three precision on-farm water management strategies to improve water use efficiency and reduce waste in agriculture. In doing so, this research aims to support sustainable agricultural practices, meet USDA AFRI (Agriculture and Food Research Initiative) priority area "Agriculture Systems and Technology", and reach UN Sustainability Goal 6 (Clean Water and Sanitation), Goal 9 (Industry, Innovation, and Infrastructure), and Goal 12 (Responsible Consumption and Production). In this paper, the precision irrigation techniques, drip irrigation and variable-rate irrigation (VRI) systems will be discussed. Next, drought-resistant crops (DRCs) and their benefits to farmers when relation to waste prevention will be investigated. Lastly, the study will explore modular floating covers as a form of dam evaporation control. Although these methods of preserving water and increasing water efficiency are extremely beneficial while already having been implemented for on-farm systems, there is room for further technological improvements.

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Introduction

While 70% of the Earth's surface is water, only 1% of it is accessible freshwater (Youssef & Khodzinskaya, 2019). Along with the growing human population and desertification, freshwater is becoming a scarce commodity in many nations. Moreover, the rapid acceleration of industrial activity has led to excessive consumption of clean groundwater and pollution of natural water resources such as lakes and rivers, causing a global water crisis (Velasco-Muñoz et al., 2018). According to the World Resources Institute, at least 25 nations face extremely high-water stress, meaning that they use at least 80% of their available water supply annually (World Resources Institute, 2023). Additionally, 1.1 billion people worldwide suffer from a lack of access to freshwater (World Wildlife Fund, 2025). The agriculture sector is the largest consumer of freshwater globally. With irrigation supporting crops and livestock being the primary driver for water consumption, the industry consumes approximately 70% of total freshwater withdrawals (UNESCO, 2024). Without changes to practice and sustainability, the growing crisis will threaten global food security, the future of agriculture, and exacerbate the struggles of millions who lack access to safe, clean water.

Purpose

The goal of this study is to investigate the three most optimal strategies for precision on-farm water management to enhance water use efficiency and reduce waste. Precision strategies utilize technology to reduce the need for human input and make a system more effective. The proposed strategies include: (1) precision irrigation techniques, (2) drought-resistant crops, and (3) dam control of evaporation (see Fig. 1). The research supports the advancement of sustainable agricultural practices and aligns with USDA AFRI priority area, "Agriculture Systems and Technology," as well as with UN Sustainable Development Goals: 6 (Clean Water and Sanitation), 9 (Industry, Innovation, and Infrastructure), and 12 (Responsible Consumption and Production). Additionally, this endeavor serves as a reference for farmers, entrepreneurs, and stakeholders to achieve sustainable water practices towards an economically and environmentally viable future in agriculture.

Figure 1.

Structure of the strategies investigated and presented in this article.

Methods

To identify the most effective precision on-farm water management strategies, this study was based on a review of existing literature, including peer-reviewed articles, data from notable agricultural websites, governmental websites, and academic institutions. The researchers consistently used up-to-date data sources and designed a search strategy using the 'Google Scholar' search engine. This strategy used a set of subject-representative keywords that included "water management", "precision agriculture", and "environmental". Additionally, the researchers saw a lack of a critical approach as a potential setback but addressed this by using a thorough evaluation and summarization of information. By putting all possible solutions up to the same standards, the researchers prevented bias and ensured that every source was compared equally.

Precision Irrigation Techniques

Precision Irrigation Techniques: Drip Irrigation

What It Is and How It Works. Drip irrigation is a modern agricultural technique that uses concentrated, precise distributions to water the roots of a plant. This allows optimal soil moisture in crops while minimizing water waste (Shareef et al., 2019). Unlike conventional or furrow irrigation, drip irrigation can reduce water consumption by 20-60%. Additionally, a well-designed drip irrigation system loses almost no water to runoff, deep percolation, or evaporation (Shock, 2020). In 2015, irrigation accounted for over 42% of the United States' water use in agriculture (Hrozencik, 2025). Because irrigation is such a major source of water consumption, large-scale adaptation of drip irrigation methods has great potential to reduce the water crisis. A typical drip irrigation system is made up of a network of pipes and emitters to deliver water directly to crops (Shareef et al., 2019). Although the specific drip irrigation system depends on the crops, soil type, farm, and other variables, a generic drip irrigation system typically entails the following procedure (see Fig. 2):

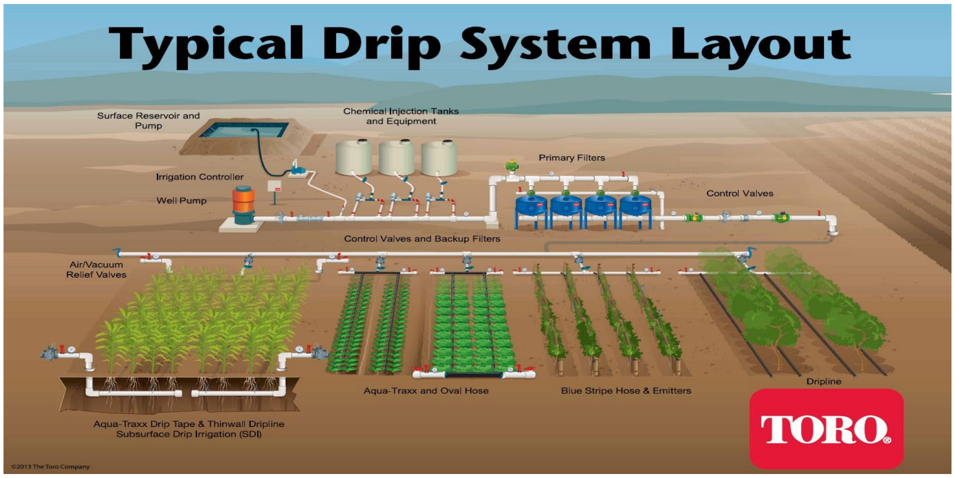
1. Water is drawn from a source, such as a water tank or reservoir, and pumped through an irrigation controller. A multi-stage filtration setup may be used, including chemical treatment (Shareef et al., 2019).

2. A fertilization unit that injects soluble fertilizers into the water supply may be implemented.

3. Control valves adjust water pressure to a lower rate. These prevent water overuse and inconsistent flow rates. The water runs through the pipes and is delivered to the root zones of each plant through emitters according to the crop spacing and root depth.

4. The system can be operated by hand or automated using timers, smart irrigation, and moisture sensors. Automated systems are typically more accurate and water-efficient (Van De Zande et al., 2024).

Figure 2.



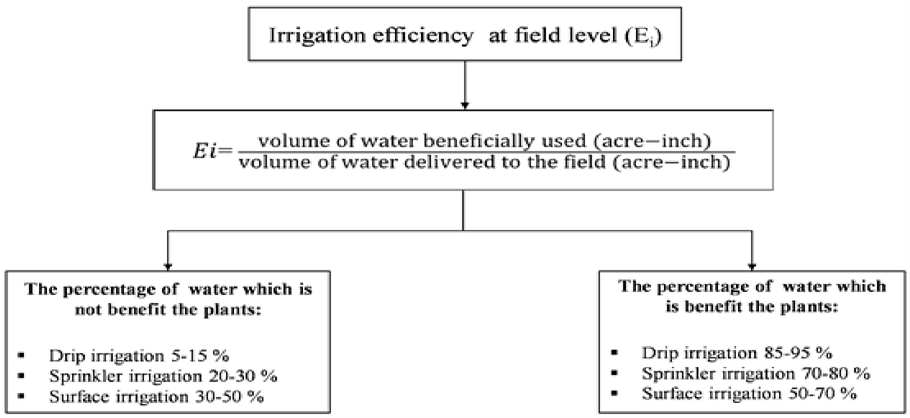
A typical drip irrigation system layout (Tavares, 2021).

Implementation. Drip irrigation has countless benefits, including disease prevention by reducing water contact on leaves, high water application efficiency, the ability to irrigate irregularly shaped fields, and increasing crop yield (Freie Universität Berlin, 2012). With its advantages, the prevalence of drip irrigation on farms has risen. According to the 2018 USDA statistics service, 72% of all irrigated cropland acres in the western U.S. used pressurized irrigation systems (Hrozencik, 2025). On a global scale, only about 5% of countries are implementing the irrigation method (Philipp, 2023). However, global adoption of the irrigation technique is seeing steady growth. From 1992 to 2012, the area under drip and other “micro” irrigation methods rose from 1.6 million hectares to over 10.3 million. Additionally, there is significant uptake of drip irrigation by countries experiencing high water stress, such as Morocco and Pakistan, which are seeing promising results (Post Carbon Institute, 2012).

Implementing drip irrigation varies based on farm type, crops, soil, and other environmental factors. Fortunately, drip irrigation is a flexible system and can be integrated into any agricultural context without disturbing related operations. Large-scale farms often adopt fully automated systems, while smaller farms often adopt drip irrigation in more targeted ways (Van De Zande et al., 2024). Because drip irrigation is most successful when it complements existing farm systems rather than disrupting them, water content, nutrients, pressure, and filtration can all be adjusted to fit the farm's needs (Freie Universität Berlin, 2012).

Environmental Viability. Countries such as Israel have implemented widespread drip irrigation, which has greatly mitigated the impacts of drought and climate change on agricultural production (Post Carbon Institute, 2012). The process boasts a crop benefit percentage of 85-95% compared to the 70-80% of sprinkler irrigation and the even lower 50-70% of surface irrigation (Shareef et al., 2019). By targeting root zones directly, water use efficiency exceeds traditional systems and controls surface water runoff that can potentially disrupt topsoil and nutrients (Chen et al., 2023). Furthermore, drip irrigation uses less energy than sprinkler systems because less water is pumped and pressurized. This makes it an environmentally viable precision strategy that can efficiently save and manage water and energy (See Fig. 3).

Figure 3.



A chart illustrating the irrigation efficiency of drip irrigation in comparison to other methods (Shareef et al., 2019).

Economic. Installing a drip irrigation system costs around $500 to $1200 in initial investment per acre (Shock, 2020). Although this may be a high cost, it leaves behind numerous economically favorable yields that make it a profitable investment. Automated systems mean a lower labor cost and a reduced need for manual irrigation. Additionally, the system offers high input efficiency for fertilizer, chemical treatment, and water. Because of the promising input, no additional resources or money are spent to account for this. Overall, efficient irrigation means better crops leading to higher productivity and marketing, making drip irrigation an ideal economic strategy.

Possible Limitations. Despite its numerous advantages, drip irrigation has drawbacks. These include emitter clogging, limited water distribution, and sun damage to tubes. Additionally, without expert consultation on land topography, soil, and water, farmers may lack the necessary skills to run drip irrigation equipment. However, with careful study, installation, and management, these drawbacks can easily be avoided (Freie Universität Berlin, 2012).

Precision Irrigation Techniques: Variable-Rate Irrigation (VRI)

What It Is and How It Works. Another type of precision irrigation technique is variable-rate irrigation (VRI) (See Fig. 4). Recent advancements in sensor technologies and artificial intelligence have enabled increased global diffusion of VRI technology. There are two types: map-based VRI and sensor-based VRI (Southeast Climate, n.d.). VRI significantly reduces waste when watering crops and improves water efficiency by watering only when needed, rather than routinely, as is the case on most farms. Map-based VRI is the most common type. It requires geospatial data such as soil type and crop yield, which can be costly to collect. It also requires a professional who can generate maps using a Differential Global Positioning System (DGPS) to determine what areas of a field need watering. On the other hand, sensor-based VRI does not require an operator but utilizes an algorithm to efficiently and effectively water areas that need it. The technology is relatively new, but it requires less human input because it uses an algorithm. Although both achieve the same goal, they use different methods of irrigation to increase water efficiency and reduce water waste (Sharma et al., 2025).

Figure 4.

VRI-enabled pivot at University of Georgia's Stripling Irrigation Research Park is being used to vary irrigation application rates over research plots (Stripling, 2017).

Implementation. Map-based variable-rate irrigation (VRI) is already implemented around the world on large, corporate farms. However, sensor-based technology has recently gained traction and is becoming prominent due to recent technological developments. It may be difficult to implement VRI technology in developing countries where traditional practices dominate, but overall, it would likely become a success once the technology becomes widely known.

Environmental Viability. VRI technology is environmentally viable due to the amount of water conserved. Due to the precision technology, water used is greatly decreased, and there are minimal amounts of waste because crops are watered to the precise amount needed. Water efficiency in sungrass and alfalfa crops increased from 7.64% to 21.25% and from 1.13% to 7.63% respectively (Li et al., 2023). With many traditional farms using upwards of hundreds of thousands of gallons of water, significant amounts will be saved with the use of VRI systems.

Possible Limitations. Although technology is environmentally sustainable, machines occasionally malfunction. A machine could malfunction during use or become damaged beyond repair when sitting in storage. Additionally, machines may lag or function unreliably in certain areas. This is because all of the technology is relatively new, and there is more research to be done before it can run without errors or malfunctions (Shi et al., 2019). Issues may arise in map-based systems depending on the quality of the maps or the map technology. If a sensor does not update the irrigation system in real time, it could irrigate the wrong area or not irrigate at all (Shi et al., 2019).

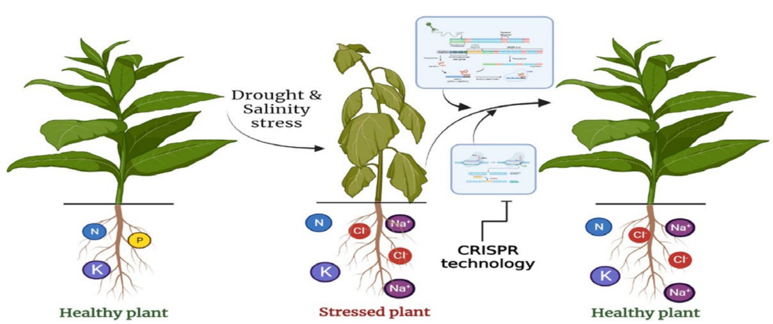
Drought-Resistant Crops (DRCs)

What It Is and How It Works. A second strategy to reduce waste and increase water efficiency is to implement drought-resistant crops (DRCs). With the use of genetic engineering and biotechnology, including CRISPR and genomic selection, DRCs have significantly evolved (Khan et al., 2019). CRISPR is a biotechnology method used to modify an enzyme called Cas9 to enhance the plant's ability to withstand dry conditions. CRISPR uses a guide RNA to direct the Cas9 enzyme to a specific genomic sequence (CRISPR Therapeutics, 2024). Genomic selection is a breeding method where genetic markers are associated with traits used to estimate the breeding value of a plant to enhance various traits such as drought resistance and water retention. Before genetic selection can be used, specific morphological traits, yield performance, and other data must be obtained. Other data needed include water use efficiency metrics, physiological criteria, and biochemical criteria (Khan et al., 2016). Although these methods use technologies, they have the same common goal of creating crops to use water in the most efficient way possible.

Implementation. Implementing drought-resistant crops (DRCs) is a lengthy process due to trying to find varieties, adopting specific agronomic practices, and utilizing every technological advancement (Caño-Delgado et al., 2020). DRCs are being implemented globally, but primarily in regions that have water scarcity or a drier climate. In the United States, they are used in the western Corn Belt, in states such as Kansas, Texas, and Nebraska. Implementation of DRCs will conserve water because they can survive longer dry periods. However, many countries might reject the DRCs due to cultural or religious bias against the genetic modification of a living organism.

Environmental Viability. Drought-resistant crops (DRCs) are environmentally viable because they help to conserve water and reduce water waste (See Fig. 5). These crops can go longer without water and produce the same, if not more, yield. DRCs maintain productivity and reduce crop failure because of being able to survive the dry conditions (Ameer, 2024).

Figure 5.



Stress-tolerant mutants have been developed by using the CRISPR tool (Bishnu Angon et al., 2023).

Limitations. Although DRCs are more sustainable for the environment, there are some possible concerns. When DRCs are planted in environments with ideal water conditions, they can underperform. Additionally, farmers may not be able to afford DRCs because the technology is relatively new and is accessible mostly to large corporations at the moment. Lastly, DRCs could be at higher risk for pest and insect problems (Raghu et al., 2025).

Dam Evaporation Control

Modular Floating Cover

What It Is and How It Works. Dams are crucial water reservoirs for the agricultural industry and supply water for nearly everyone; however, the evaporation of water in those dams is resulting in high economic costs and significant loss of freshwater. The third strategy to reduce water waste is dam evaporation control, specifically utilizing modular floating covers in large water reservoirs. The modular floating cover method uses small modules that freely float in water while not completely covering the surface. The modules are usually spherical or cylindrical objects made with polypropylene and high-density polyethylene plastic, which meet food-grade standards. By floating on the water's surface and reducing exposure to sunlight and wind, these modules efficiently prevent the evaporation of the water (Youssef & Khodzinskaya, 2019).

Implementations. Currently, floating modular covers are implemented in various water reservoirs, from large dams to smaller water reservoirs. The method is especially prevalent in arid regions with water scarcity, such as Australia, the United Arab Emirates, Saudi Arabia, and California (Schmidt et al., 2020). For example, the Los Angeles Department of Water and Power (LADWP) implemented floating modules to reduce evaporation and protect water quality from UV rays (Department of Neighborhood Empowerment, 2015).

Environmental Viability. Compared to direct methods of blocking the surface, such as continuous floating modules, which 100% cover up the surface with a single module, modular floating covers have space between the modules. These gaps allow for air circulation above the water, increasing the transfer of dissolved oxygen and enhancing water quality (Youssef & Khodzinskaya, 2019). Some modules have small holes to expel air from the water surface that the module is covering, which also assists in enhancing oxygen diffusion into the water. The modules are also effective in preventing water evaporation from the surface. In a trial at NorthParkes Rio Tinto Mine in New South Wales, Australia, when 90% of the surface area was covered by floating modules, 85% of evaporation was reduced, compared to the control trial with no covers (Schmidt et al., 2020). Another trial concluded that approximately 90% of the evaporation is prevented with full coverage of the surface (Zang et al., 2010). Moreover, because the modules can permanently float around the surface with little restriction, they require less maintenance cost than chemical methods, which require regular deployments to maintain their effectiveness (Youssef & Khodzinskaya, 2019).

Possible Limitations. Despite the benefits of preventing water evaporation through modular floating covers (MFCs), there are financial barriers that hold back people from implementing this method. In general, the capital cost of newly implementing the method is around \$20-\$40/m^2, which could be a burden for individuals who own small water reservoirs (Schmidt et al., 2020). This is the reason why, even though the maintenance cost is relatively cheap, MFCs like shade balls are typically used in water reservoirs owned by municipalities or large companies.

Conclusion

Freshwater availability is declining globally due to climate change, overuse, and unsustainable agricultural practices. Through irrigation methods, such as drip irrigation and variable-rate irrigation, drought-resistant crops (DRCs), and dam control evaporation, water can be used efficiently, and water waste can be prevented. These strategies align with USDA AFRI priority area “Agriculture Systems and Technology” and United Nations Sustainable Development Goals 6, 9, and 12 to make the world a better place for all by ensuring access to clean and potable water. Using drip irrigation, water can be conserved because the water goes straight to the roots and has little to no runoff, unlike traditional methods. With VRI, the crops are watered only when needed rather than regularly. DRCs can withstand long dry periods and survive because of gene editing through genetic selection and CRISPR technologies. Dam evaporation techniques, such as modular floating covers, conserve water by preventing evaporation and maintaining water quality. Though these strategies are the best for on-farm water management, steps towards advancement can still be taken. Technological innovations that allow for further water waste reduction, more precise systems, accurate algorithms, and further research into genetic engineering should be explored.

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