

ENHANCING WATER PRODUCTIVITY UNDER CLIMATE CHANGE: ADVANCES IN PRECISION IRRIGATION, SMART TECHNOLOGIES AND SUSTAINABLE WATER MANAGEMENT

Ashutosh Pradhan¹, Suchismita Tripathy^{2*}, Dharani Dhar Pradhan³, Sajeel Kumar Biswas⁴, Anita Mahapatra⁵, Devashish Dash⁶, Akshaya Kumar Sethy⁷, Asim Chandra Dash⁸, Anupama Baliarsingh⁹, S.K. Sahoo¹⁰, Jyoti Rekha Patnaik¹¹

¹M.Sc. Research Scholar, Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India, Email: jeevanjyoti.ap11@gmail.com, <https://orcid.org/0009-0007-7734-2550>

^{2*}Associate Professor, Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India, Email: suchismita.agro@ouat.ac.in, <https://orcid.org/0009-0009-3611-9699>

³Ph.D. Research Scholar, Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India, Email: dharanidhar.rs23@ouat.ac.in, <https://orcid.org/0009-0008-4316-4212>

⁴Senior Scientist, RRTSS, Kirei, Odisha, rrtss.kirei@ouat.ac.in, <https://orcid.org/0009-0004-9399-5314>

⁵Senior Scientist, AICRP on Sunflower, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India, E-mail: anitamahapatra@ouat.ac.in, <https://orcid.org/0000-0003-0008-7284>

⁶Dept. of Extension Education, Department of Extension Education, C.V. Ramam Global University, Bhubaneswar-752054, Email: drdebashis.ag@cgu-odisha.ac.in, <https://orcid.org/0000-0003-3605-0002>

⁷Senior Scientist, AICRP on Groundnut, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India, E-mail: aksethy@ouat.ac.in, <https://orcid.org/0009-0001-1381-1166>

⁸Assistant Professor, Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India, Email: acdash@ouat.ac.in, <https://orcid.org/0009-0002-4398-6351>

⁹Professor, Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India, Email: anupamabs@ouat.ac.in, <https://orcid.org/0009-0004-0324-0306>

¹⁰Scientist, AICRP on Niger, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India, Email: srimanta@ouat.ac.in, <https://orcid.org/0009-0001-5045-7688>

¹¹Assistant Professor, Department of Agronomy, Odisha University of Agriculture and Technology, Bhubaneswar-751003, India. Email: jyotirekha@ouat.ac.in, <https://orcid.org/0009-0005-1277-2918>

ABSTRACT

Climate change is intensifying pressure on already scarce water resources and making both irrigated and rainfed agriculture, particularly in arid and semi-arid regions, increasingly uncertain. Improving water productivity (WP), the yield or economic value of a crop per unit of water used, has therefore become a central strategy for climate-resilient agriculture. Conventional irrigation systems lose large volumes of water through evaporation, runoff, seepage and deep percolation, which keeps WP low. This review examines the principal factors that determine WP, namely climate and weather, soil properties, crop species and variety, irrigation method and scheduling, agronomic practices and conveyance losses, and evaluates strategies and technologies that reduce water losses and raise WP under climate change. Canal lining, efficient irrigation systems, science-based irrigation scheduling, soil and crop management and water reuse provide the foundation for reducing non-beneficial water use. Modern technologies, including hydroponics, aquaponics, sprinkler and drip irrigation (including gravity-fed TIPA systems), precision (smart) irrigation, soil-water tension sensors (Chameleon), Tal-Ya trays, crop simulation modelling (AquaCrop), water footprint assessment and conservation agriculture, are assessed for their ability to match water supply with crop demand and maximise productive transpiration. Reported water savings range from 20–30% for sensor-based control added to sprinkler systems to 30–70% for drip irrigation and up to 90% for recirculating aquaponic systems. Used together, these technologies enable real-time monitoring, controlled water application and informed decision-making, reducing irrigation water use while maintaining or increasing yields. Combining modern water management technologies with climate-smart agronomic practices is essential for improving WP, climate resilience and the sustainability of agricultural production in water-limited environments.

KEYWORDS: AquaCrop, climate change, drip irrigation, precision irrigation, water footprint, water productivity

1. INTRODUCTION

Climate change is increasing pressure on already scarce water resources and threatening the viability of irrigated and rainfed agricultural systems, particularly in arid and semi-arid regions (FAO, 2020). Agriculture accounts for about 70% of global freshwater withdrawals, making it highly exposed to changes in water availability under a changing climate. Improving water productivity (WP), the ratio of crop output to water consumed, has therefore emerged as a key strategy for building resilience in agriculture (Molden et al., 2010).

Conventional irrigation is commonly associated with low application efficiency and large losses through evaporation, runoff and deep drainage, which keep crop WP below its potential (Howell, 2001). Climate change further raises crop water demand while reducing the reliability of water supplies (Rockström et al., 2010). There is thus a growing need for advanced water management technologies.

Recent advances in precision agriculture, remote sensing and information and communication technologies now allow crop water demand and soil–plant–atmosphere conditions to be assessed in real time (Khan et al., 2021). Micro-irrigation systems, soil moisture sensors, automated irrigation, satellite-based estimation of evapotranspiration and crop simulation

models such as AquaCrop support deficit and precision irrigation aimed at maximising yield per unit of water applied (Pereira et al., 2012; Raes et al., 2018). Decision-support systems that integrate weather forecasts with crop simulation further enable adaptive irrigation management under climatic uncertainty (Jones et al., 2017).

Integrating modern technologies into agricultural water management is therefore an important option for improving WP under emerging climate change scenarios, by increasing irrigation system efficiency, reducing water losses and better matching water supply with crop water demand. This review examines (i) the factors that influence WP, (ii) strategies for minimising water losses and (iii) modern technologies for enhancing WP, and discusses their potential contribution to climate-resilient agriculture.

2. Factors Influencing Water Productivity

Water productivity, expressed as crop yield or economic value per unit of water, is governed by a set of climatic, soil, crop and management factors (Molden et al., 2010; FAO, 2017). Understanding these factors is essential for developing approaches that produce more food with less water in a climate-stressed environment. Their interrelationships are summarised in Fig. 1.

Climate change: higher temperature, erratic rainfall, more frequent drought

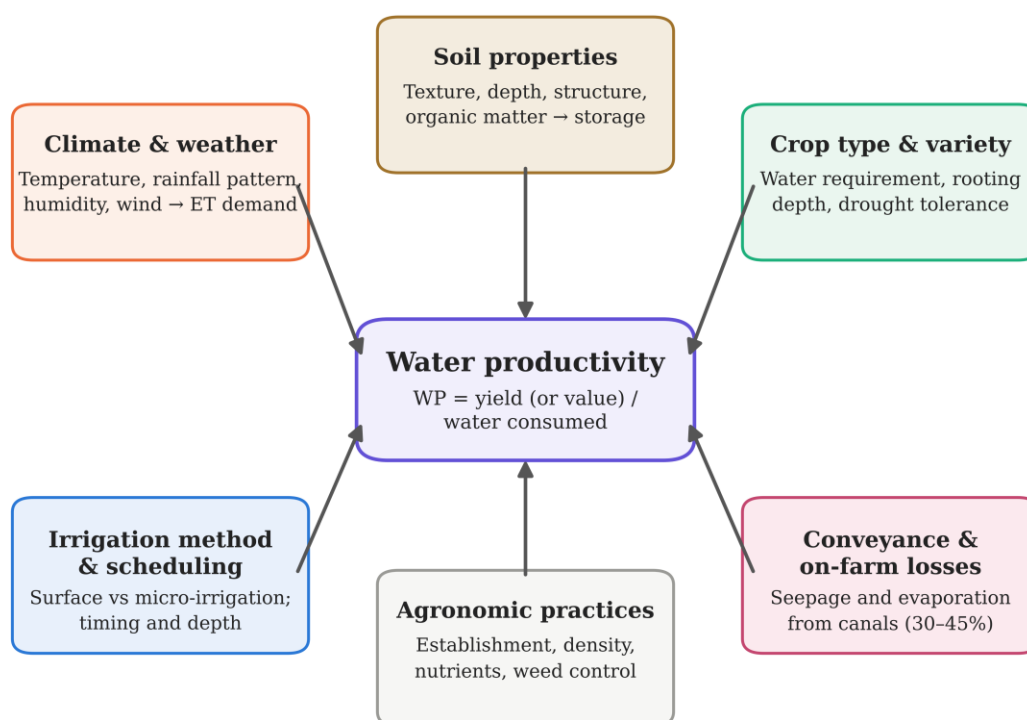


Figure 1. Major factors influencing agricultural water productivity (WP) under climate change. Arrows indicate the influence of each factor group on WP; ET, evapotranspiration. Conveyance losses in earthen channels from Howell (2001).

2.1 Climate and weather

Temperature, rainfall pattern, humidity and wind speed strongly affect crop water use and WP. Higher temperatures and drying winds accelerate evapotranspiration, increasing crop water requirements and widening WP gaps unless irrigation is adjusted accordingly (Allen et al., 1998; FAO, 2017). Erratic rainfall and drought reduce effective rainfall and increase dependence on irrigation, lowering WP in both rainfed and irrigated systems (FAO, 2020; Rockström et al., 2010).

2.2 Soil properties

Soil texture, structure, depth and organic matter content determine how much water can be stored and supplied to crops. Sandy soils have low water-holding capacity and high percolation rates, leading to deep percolation losses, whereas poorly managed clay soils are prone to runoff and inadequate aeration (FAO, 2017). Degraded soils low in organic matter retain less water, so a smaller fraction of available water contributes to productive transpiration rather than to evaporation (Molden et al., 2010).

2.3 Crop type and variety

Crops and varieties differ widely in water requirement and in the efficiency with which they convert water into biomass and yield. Millets and sorghum require less irrigation (blue) water per unit of output than rice or sugarcane (FAO, 2017). Deep-rooted and drought-tolerant varieties can exploit soil water more effectively and sustain productivity under water-limited conditions, thereby increasing WP (FAO, 2013; Rockström et al., 2010).

2.4 Irrigation method and scheduling

The irrigation method is a critical determinant of WP. Surface irrigation is often associated with large losses through evaporation, runoff and percolation, whereas micro-irrigation systems such as drip and sprinkler apply water more efficiently to the root zone (Howell, 2001; FAO, 2017). Poorly timed irrigation and over-irrigation reduce WP by increasing non-beneficial water use without a corresponding increase in yield (Molden et al., 2010).

2.5 Agronomic management practices

Crop establishment method, plant density, fertilization and weed control significantly affect crop water use efficiency. Inadequate fertility can limit growth even when water is sufficient, resulting in low yield per unit of water (FAO, 2017). Weeds compete for water and nutrients, and inappropriate spacing increases soil evaporation, reducing the beneficial use of applied water (Molden et al., 2010).

2.6 Water conveyance and on-farm losses

Substantial water is lost before it reaches the crop, through seepage and evaporation from canals. Losses in earthen channels can range from 30 to 45% (Howell, 2001). Such losses directly reduce WP at the system level even when field-level WP has improved (FAO, 2017).

3. Strategies for Minimising Water Losses in Agriculture

Agriculture is the largest consumer of freshwater, accounting for about 70% of total withdrawals (FAO, 2017; Molden et al., 2010). A substantial share of this water is lost through seepage, evaporation, runoff and inefficient application before it can be used for plant growth (FAO, 2017; Molden et al., 2010). Minimising these losses is critical for improving WP and ensuring food security as the climate changes. The main strategies, the loss pathways they address and their reported effects are summarised in Table 1.

3.1 Improving water conveyance infrastructure

Large irrigation losses occur during conveyance from source to field, especially in unlined earthen canals and open channels. Lining canals with concrete, brick or geomembranes and converting open channels to piped systems can reduce seepage losses by 60–90% (Howell, 2001; FAO, 2017), increasing the volume of water delivered to farms and improving overall irrigation efficiency.

3.2 Adopting efficient irrigation methods

Conventional surface irrigation is prone to high evaporation, runoff and deep percolation losses. Micro-irrigation systems, including drip and sprinkler irrigation, deliver water to the root zone in a controlled manner and reduce non-beneficial water use (Howell, 2001). These systems improve application efficiency and allow farmers to produce more crop per unit of water (Molden et al., 2010).

3.3 Science-based irrigation scheduling

Irrigation applied without regard to crop water requirement leads to over-irrigation and waste. Scheduling based on crop growth stage, soil moisture status and weather ensures that water is applied only when needed (FAO, 2017), avoiding unnecessary irrigation and drainage and evaporation losses while maintaining soil moisture at levels optimal for growth (Molden et al., 2010).

3.4 Soil and field water management

Land levelling, mulching, conservation tillage and organic matter application increase infiltration and soil water-holding capacity and thereby reduce runoff and evaporation losses (FAO, 2017). Raised-bed planting and appropriate field design promote uniform water distribution and prevent waterlogging and deep percolation (Howell, 2001).

3.5 Crop and cropping system management

Selecting crops and varieties suited to local climatic and soil conditions avoids wasteful water use. Drought-tolerant and short-duration varieties require less water and sustain yields under water limitation (FAO, 2013; Rockström et al., 2010). Crop diversification and intercropping can further reduce total seasonal water losses (Molden et al., 2010).

3.6 Water reuse

Reuse of treated wastewater and drainage water for irrigation reduces dependence on freshwater and lowers conveyance losses by using water close to where it is generated (FAO, 2017). When properly managed, such practices conserve water without compromising crop productivity.

Table 1. Strategies for minimising agricultural water losses, the loss pathways addressed and their reported effects

Strategy	Main practices	Loss pathway addressed	Reported effect	Source
Conveyance improvement	Canal lining (concrete, brick, geomembrane); piped distribution	Seepage, evaporation in canals	60–90% less seepage loss	Howell (2001); FAO (2017)

Strategy	Main practices	Loss pathway addressed	Reported effect	Source
Efficient irrigation methods	Drip, sprinkler, micro-irrigation	Evaporation, runoff, deep percolation	Higher application efficiency; more crop per drop	Howell (2001); Molden et al. (2010)
Irrigation scheduling	Crop-stage, soil-moisture and weather-based scheduling	Over-irrigation, drainage	Water applied only when needed	FAO (2017)
Soil and field management	Land levelling, mulching, conservation tillage, organic matter, raised beds	Runoff, soil evaporation, waterlogging	Higher infiltration and soil water storage	FAO (2017); Howell (2001)
Crop and system management	Drought-tolerant, short-duration varieties; diversification; intercropping	Excess seasonal crop water use	Stable yields with less water	FAO (2013); Rockström et al. (2010)
Water reuse	Treated wastewater and drainage water for irrigation	Freshwater demand; conveyance losses	Supplementary water supply	FAO (2017)

Effects are as reported in the cited sources; magnitudes vary with crop, soil, climate and management.

4. Modern Technologies for Enhancing Water Productivity

Enhancing WP, i.e. producing more crop or value per unit of water, requires smarter water management and more efficient cropping systems. The principal technologies currently in use are described below and compared in Table 2.

4.1 Hydroponics

Hydroponics is a soilless method of growing plants in nutrient-rich water solutions. It improves WP by eliminating the non-productive losses of soil-based agriculture, such as deep percolation and runoff. Because water is recirculated in closed or semi-closed systems, crop water use is confined largely to transpiration and minor evaporation, giving substantially higher yield per unit of water (Rajendran et al., 2024).

Hydroponics increases WP through controlled water supply, high plant density and rapid growth, which together raise biomass and economic returns per unit of water, land and time (Rajendran et al., 2024). It is particularly useful in water-deficit areas and protected cultivation where conventional irrigation is inefficient. By optimising water and nutrient supply simultaneously, hydroponics turns water from a limiting factor into a precisely controlled input.

4.2 Aquaponics

Aquaponics integrates recirculating aquaculture with hydroponics so that fish and plants are produced together in a single water-recycling system. Nutrient-rich effluent from fish rearing is biologically converted into plant-available nutrients; plant uptake in turn purifies the water, which is returned to the fish tanks. This recycling reduces dependence on freshwater and increases system WP (Okomoda et al., 2022).

Okomoda et al. (2022) reported that aquaponics can reduce water use by up to 90% compared with soil-based production, because losses are restricted to transpiration and a small amount of evaporation. The system also produces two outputs, fish and vegetables, from the same water, maximising economic and biological yield per unit of water.

4.3 Sprinkler irrigation

Sprinkler irrigation is a pressurised system that distributes water as droplets, simulating rainfall. Compared with surface methods such as flood or furrow irrigation, it provides better application uniformity and efficiency and reduces non-productive losses through evaporation and runoff. In a detailed review, Chaudhary et al. (2023) reported that sprinkler irrigation can save about 39% of water and increase WP by more than 14% relative to gravity-fed surface irrigation. When combined with automation and precision tools, such as sensor-based soil and weather monitoring, data analytics and IoT-controlled valves, sprinkler systems can save a further 20–30% of irrigation water and increase yields by 20–27% by matching water application more closely to crop demand (Chaudhary et al., 2023).

4.4 Drip irrigation

Drip irrigation is a micro-irrigation system that delivers water slowly and directly to the root zone through a network of pipes, valves, filters and emitters. By confining application to the root zone, drip systems minimise deep percolation and surface runoff and substantially improve water use efficiency compared with flood and furrow methods, which wet large areas of soil unnecessarily. Drip irrigation can reduce water use by 30–70% relative to surface methods while sustaining equal or higher yields, depending on crop and management (Banik et al., 2024). Water is retained in the active root zone for longer, increasing the share that contributes to productive transpiration (Banik et al., 2024). Drip systems can also be combined with fertigation, the simultaneous application of water and nutrients, which improves nutrient uptake efficiency

and further raises WP (Yang et al., 2023). Subsurface drip irrigation (SDI), in which laterals are buried below the soil surface, further reduces soil evaporation and is particularly effective in arid and semi-arid climates (Yang et al., 2023).

4.5 TIPA low-cost gravity drip irrigation

TIPA is a simplified, gravity-fed drip irrigation system designed for areas without pressurised water or electricity. An elevated tank supplies laterals and emitters that deliver water slowly to the root zone by gravity alone, reducing runoff, evaporation and deep percolation. Field evaluation of a small-farm gravity drip system showed high emission uniformity (generally above 85%), adequate wetting depth and diameter for vegetables and efficient delivery of water and nutrients to the root zone, confirming its suitability for water-limited smallholdings (Isikwue et al., 2016). The TIPA system has been deployed in the desert regions of Senegal to irrigate crops where no pressurised supply exists, providing a model for extending efficient irrigation across the Sahel (Frenkel, 2018).

4.6 Chameleon soil-water sensor

The Chameleon sensor, developed by CSIRO and ACIAR, measures soil water tension, i.e. the effort roots must exert to extract water, rather than volumetric water content, which makes readings easier to interpret across soil types (CSIRO, n.d.). It is inexpensive and designed for farmers, who irrigate when the tension reading exceeds crop-specific thresholds. This supports deficit and precision irrigation and prevents over-irrigation. Simple, robust sensors of this kind can help smallholders adopt smart irrigation practices.

4.7 Tal-Ya trays

Tal-Ya trays are square, serrated polypropylene trays placed around plants to reduce soil evaporation, suppress weeds and channel dew and condensation to the roots. Water savings of about 50% or more have been reported in arid environments because the tray concentrates both captured moisture and irrigation water at the plant (Tal-Ya Agriculture Solutions, n.d.). Tal-Ya is an example of a low-technology, high-impact water-saving option suited to rainfed and smallholder irrigated systems.

4.8 Precision (smart) irrigation

Precision irrigation applies water according to the actual requirement of the crop rather than a fixed calendar. It uses real-time data from soil moisture sensors, weather stations and crop indicators to determine when and how much to irrigate, reducing non-productive losses such as evaporation and deep percolation (Lakhia et al., 2024). Field sensor data are transmitted over communication networks to a central controller or cloud server, where decision algorithms automatically operate valves or pumps, creating a continuous cycle of monitoring, decision-making and application (Lakhia et al., 2024).

By delivering water only when and where it is needed, precision irrigation substantially improves WP. Lakhia et al. (2024) found that smart irrigation systems greatly reduce irrigation water use while maintaining or increasing yield. The water savings reported for precision irrigation and the other technologies discussed above are compared in Fig. 2.

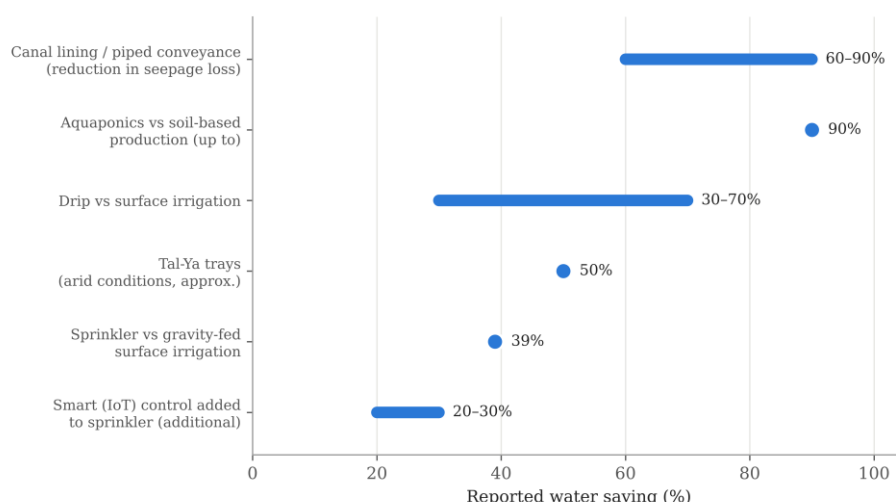


Figure 2. Reported water savings of water-saving technologies and practices. Bars show reported ranges and points show single reported values. Comparisons differ between technologies (as labelled) and are therefore indicative rather than directly comparable. Sources: Howell (2001); FAO (2017); Okomoda et al. (2022); Banik et al. (2024); Tal-Ya Agriculture Solutions (n.d.); Chaudhary et al. (2023).

4.9 AquaCrop crop model

AquaCrop is a crop growth model developed by the Food and Agriculture Organization (FAO) of the United Nations to simulate yield response to water under different management and environmental conditions (FAO, 2009). Unlike more complex models that require extensive parameterisation, AquaCrop balances simplicity, accuracy, robustness and generality, making it usable by researchers, extension workers and water managers (FAO, 2009). Its central premise is that crop yield is driven primarily by water consumption, especially transpiration, and that this relationship can be simulated across rainfed, supplemental, deficit and full irrigation regimes (FAO, 2009).

AquaCrop first simulates green canopy cover and actual transpiration from weather, soil, crop and management inputs, then converts cumulative transpiration into biomass using a normalised, crop-specific water productivity parameter, and finally derives yield from biomass through the harvest index (Fig. 3). This water-driven structure allows users to evaluate the effects of irrigation strategy, deficit irrigation, water-stress events and climate on water use and crop productivity. By linking water availability directly to growth and yield, AquaCrop is a valuable decision-support tool for optimising irrigation to maximise WP without extensive field trials (FAO, 2009), which is particularly important in water-limited areas and under climate change.

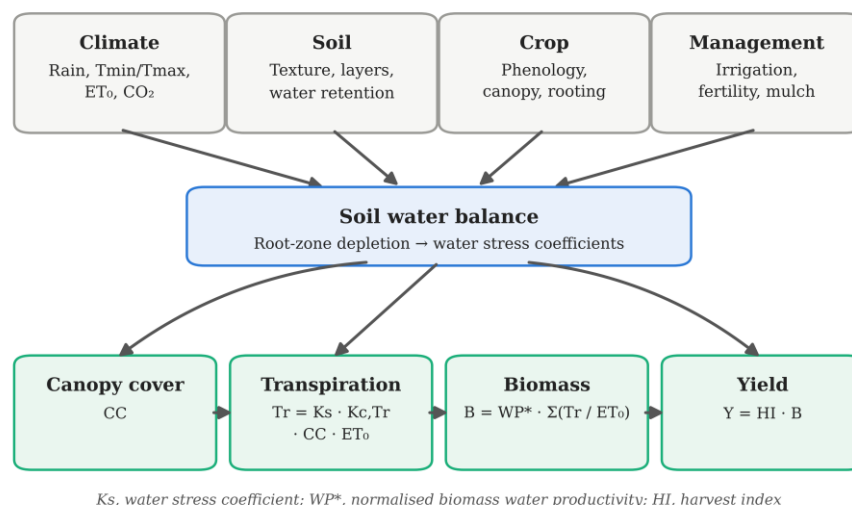


Figure 3. Simplified structure of the FAO AquaCrop model. Climate, soil, crop and management inputs drive the root-zone water balance, whose stress coefficients modify canopy development, transpiration and harvest index; biomass is computed from cumulative transpiration normalised by reference evapotranspiration (ET_0). Adapted from FAO (2009) and Raes et al. (2018).

4.10 Water footprint assessment

Water footprint assessment is an analytical approach that quantifies the total volume of water used, directly and indirectly, to produce a crop or product. It has three components: blue water (surface and groundwater used for irrigation), green water (rainwater stored in the soil and used by plants) and grey water (the volume needed to dilute pollutants to acceptable levels). Relating water use to actual production helps identify crops and production areas that consume excessive water (Hoekstra et al., 2011).

Water footprint assessment also allows comparison between crops and production systems (Fig. 4). Per tonne of product, rice and wheat have blue water footprints of about 340 m^3/t , roughly six times that of millet (57 m^3/t) and more than three times that of sorghum (103 m^3/t), because rice is flooded for long periods and both crops depend heavily on irrigation, whereas millets and sorghum rely mainly on green water (Mekonnen and Hoekstra, 2011). Total water footprints per tonne must, however, be interpreted with care: millet and sorghum have large total footprints because of their low rainfed yields, while sugarcane has a small footprint per tonne (210 m^3/t) because of its very high fresh-weight yield, even though its water demand per hectare is large (Mekonnen and Hoekstra, 2011).

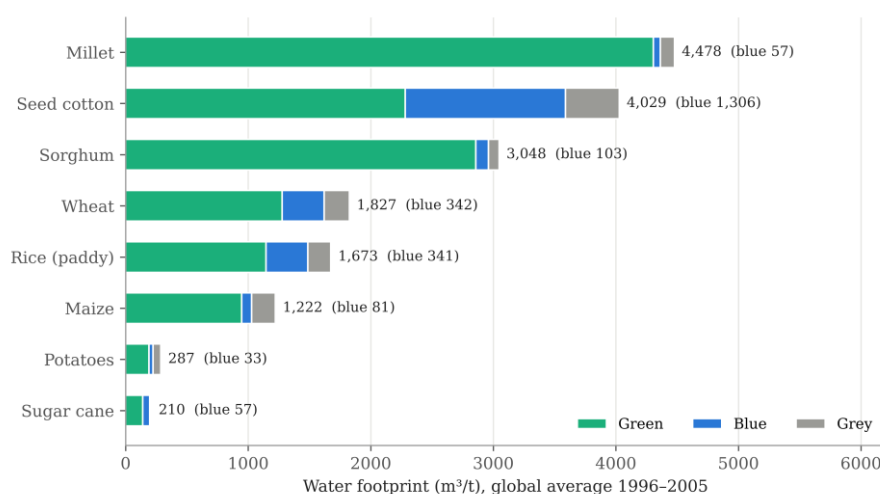


Figure 4. Global average green, blue and grey water footprints of selected crops (m^3 per tonne of product, 1996–2005). Values beside the bars give the total footprint and, in brackets, the blue (irrigation) component. Data from Mekonnen and Hoekstra (2011).

Beyond the farm, water footprint accounting can improve WP at regional and national levels. Water-scarce regions can relieve pressure on local resources by favouring crops with lower blue water footprints or by importing water-intensive products from water-abundant regions. In this way, the water footprint makes the “virtual” water embedded in products a tangible performance metric that supports better decisions on production per unit of water (Hoekstra et al., 2011).

4.11 Conservation agriculture

Conservation agriculture (CA) combines minimum soil disturbance, permanent soil cover through residue retention and crop diversification. These practices improve soil structure, increase infiltration and reduce evaporation and runoff, so that a larger fraction of rainfall and irrigation water is used for productive transpiration (FAO, 2017). CA also improves soil water retention and root growth, sustaining crop performance under variable climate and limited water.

Evidence from the Indo-Gangetic Plains confirms these benefits. In a maize–wheat system, permanent raised beds and zero tillage, both with residue retention, gave significantly higher WP and crop and system productivity than conventional tillage (farmers' practice) (Das et al., 2017). These practices also increased carbon sequestration and soil organic carbon compared with residue removal and conventional tillage, demonstrating simultaneous gains in water use efficiency and soil health (Das et al., 2017). CA can therefore be regarded as a system-level technology that conserves water in the soil–plant continuum while improving productivity and sustainability.

Table 2. Comparison of modern technologies for enhancing water productivity

Technology	Principle of water saving	Reported performance	Best suited to	Source
Hydroponics	Soiless, recirculating nutrient solution; no percolation or runoff	Much higher yield per unit water	Protected cultivation; water-scarce peri-urban areas	Rajendran et al. (2024)
Aquaponics	Fish–plant recirculation; losses limited to transpiration	Up to 90% less water than soil-based	Integrated fish–vegetable units	Okomoda et al. (2022)
Sprinkler irrigation	Uniform pressurised application	≈39% water saving; WP >14% higher	Field crops on light or undulating soils	Chaudhary et al. (2023)
Drip / subsurface drip	Root-zone application; fertigation	30–70% water saving	Horticultural and row crops; arid zones	Banik et al. (2024); Yang et al. (2023)
TIPA gravity drip	Gravity-fed drip; no pump or power	Emission uniformity >85%	Smallholders without power or pressure	Isikwue et al. (2016)
Chameleon sensor	Soil water tension thresholds for scheduling	Prevents over-irrigation	Smallholder scheduling	CSIRO (n.d.)
Tal-Ya trays	Reduce evaporation; harvest dew	≈50% water saving (arid)	Rainfed and small irrigated plots	Tal-Ya (n.d.)
Precision (smart) irrigation	Sensor–controller–actuator feedback loop	20–30% extra saving; yield +20–27%	Commercial and high-value farms	Lakhier et al. (2024); Chaudhary et al. (2023)
AquaCrop model	Simulates yield response to water	Optimises irrigation strategies	Planning, research and extension	FAO (2009)
Water footprint	Accounts green, blue and grey water	Identifies water-intensive crops	Regional planning and policy	Hoekstra et al. (2011)
Conservation agriculture	Zero tillage, residue cover, rotation	Higher WP and SOC	Irrigated and rainfed systems	Das et al. (2017)

WP, water productivity; SOC, soil organic carbon. Performance values are as reported in the cited sources and depend on crop, climate and management.

5. CONCLUSION

Climate change has intensified pressure on limited water resources, making improvement of agricultural WP central to future food security. Conventional irrigation and crop management systems are struggling to cope with rising evapotranspiration, rainfall variability and declining water availability. This review shows that WP is determined by a complex set of factors involving climate, soil, crop characteristics, irrigation systems and agronomic practices, together

with substantial conveyance and on-farm losses. These factors must be addressed in an integrated manner to produce more food with less water under climate change.

Improving conveyance infrastructure, adopting efficient irrigation systems, applying science-based irrigation scheduling and improving soil and field water management form the foundation for higher WP. Crop and cropping system management, including drought-tolerant varieties, diversification and intercropping, further reduces non-beneficial water use and increases the share of water used for productive transpiration. Reuse of treated wastewater and drainage water provides an important supplementary supply in water-scarce areas.

Modern technologies now provide powerful tools for implementing these strategies. Hydroponics and aquaponics demonstrate how closed-loop systems can greatly reduce water use while raising biological and economic productivity per unit of water. Sprinkler and drip irrigation, particularly when combined with fertigation and subsurface placement, markedly improve application efficiency and reduce evaporation and deep percolation. Low-cost innovations such as TIPA gravity drip, Chameleon sensors and Tal-Ya trays show the potential of scalable, farmer-friendly solutions for smallholder and rainfed systems.

Precision irrigation is a significant advance, combining real-time field information with automated decisions so that water is applied only when and where crops need it. Decision-support tools such as AquaCrop provide a scientific framework for evaluating irrigation options and climate scenarios without costly trial-and-error experimentation, while water footprint assessment offers a transparent basis for comparing crops and production systems and for aligning agricultural production and trade with regional water resources. Conservation agriculture integrates many of these benefits at the system level, improving water productivity together with soil health and carbon sequestration.

In summary, combining modern technologies with sound agronomic and soil management offers a clear pathway to climate-resilient agriculture. By aligning water supply with crop demand, minimising non-beneficial losses and maximising productive transpiration, these approaches can substantially improve WP. Future research and development should focus on improving farmers' access to these technologies, strengthening institutional support and building farmer capacity, so that water can be transformed from a limiting resource into a managed one and sustainable agricultural production maintained in a changing climate.

REFERENCES

1. Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). Crop evapotranspiration: Guidelines for computing crop water requirements (FAO Irrigation and Drainage Paper No. 56). Food and Agriculture Organization of the United Nations, Rome.
2. CSIRO. (n.d.). Chameleon soil water sensor. Commonwealth Scientific and Industrial Research Organisation. <https://www.csiro.au/en/research/plants/crops/farming-systems/chameleon-soil-water-sensor>
3. Das, T. K., Saharawat, Y. S., Bhattacharyya, R., Sudhishri, S., Bandyopadhyay, K. K., Sharma, A. R., & Jat, M. L. (2017). Conservation agriculture effects on crop and water productivity, profitability and soil organic carbon accumulation under a maize–wheat cropping system in the North-western Indo-Gangetic Plains. *Agricultural Water Management*, 183, 24–34. <https://doi.org/10.1016/j.agwat.2016.11.002>
4. FAO. (2009). AquaCrop: The FAO crop model to simulate yield response to water. Food and Agriculture Organization of the United Nations, Rome.
5. FAO. (2013). Climate-smart agriculture sourcebook. Food and Agriculture Organization of the United Nations, Rome.
6. FAO. (2017). Water for sustainable food and agriculture. Food and Agriculture Organization of the United Nations, Rome.
7. FAO. (2020). The state of food and agriculture 2020: Overcoming water challenges in agriculture. Food and Agriculture Organization of the United Nations, Rome.
8. Frenkel, S. (2018). Drip irrigation, blockchain technology and peace in the Middle East. *Times of Israel Blog*. <https://blogs.timesofisrael.com/drip-irrigation-blockchain-technology-and-peace-in-the-middle-east/>
9. Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2011). The water footprint assessment manual: Setting the global standard. Earthscan, London.
10. Howell, T. A. (2001). Enhancing water use efficiency in irrigated agriculture. *Agronomy Journal*, 93(2), 281–289.
11. Isikwue, M. O., Ochedikwu, A. E. F., & Onoja, S. B. (2016). Small farm gravity drip irrigation system for crop production. *Greener Journal of Science, Engineering and Technological Research*, 6(2), 48–54.
12. Jones, J. W., et al. (2017). Toward a new generation of agricultural system data, models, and knowledge products: State of agricultural systems science. *Agricultural Systems*, 155, 269–288.
13. Khan, A., Hussain, F., & Raza, A. (2021). Precision irrigation and water productivity: A review. *Agricultural Water Management*, 245, 106658. <https://doi.org/10.1016/j.agwat.2020.106658>
14. Lakhiar, I. A., Yan, H., Zhang, J., Wang, G., He, B., Hao, B., Han, Y., Wang, B., Bao, R., & Syed, T. N. (2024). A review of precision irrigation water-saving technology under changing climate for enhancing water use efficiency, crop yield, and environmental footprints. *Agriculture*, 14(7), 1141.
15. Mekonnen, M. M., & Hoekstra, A. Y. (2011). The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences*, 15(5), 1577–1600. <https://doi.org/10.5194/hess-15-1577-2011>
16. Molden, D., et al. (2010). Improving agricultural water productivity: Between optimism and caution. *Agricultural Water Management*, 97(4), 528–535.
17. Okomoda, V. T., Oladimeji, S. A., Solomon, S. G., Olufeagba, S. O., Ogah, S. I., & Ikhwanuddin, M. (2022). Aquaponics production system: A review of historical perspective, opportunities, and challenges of its adoption. *Food Science & Nutrition*, 11(3), 1157–1165. <https://doi.org/10.1002/fsn3.3154>

18. Pereira, L. S., Cordery, I., & Iacovides, I. (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agricultural Water Management*, 108, 39–51.
19. Raes, D., Steduto, P., Hsiao, T. C., & Fereres, E. (2018). AquaCrop—The FAO crop model to simulate yield response to water: II. Main algorithms and software description. *Agronomy Journal*, 101(3), 438–447.
20. Rajendran, S., Domalachenpa, T., Arora, H., Li, P., Sharma, A., & Rajauria, G. (2024). Hydroponics: Exploring innovative sustainable technologies and applications across crop production, with emphasis on potato mini-tuber cultivation. *Heliyon*, 10(5), e26823. <https://doi.org/10.1016/j.heliyon.2024.e26823>
21. Rockström, J., et al. (2010). Managing water in rainfed agriculture—The need for a paradigm shift. *Agricultural Water Management*, 97(4), 543–550.
22. Tal-Ya Agriculture Solutions. (n.d.). Tal-Ya trays: Product information and case studies. <https://www.tal-ya.com/>