Available online at www.agrifarming.org

DOI: http://dx.doi.org/10.18782/2582-7146.325

ISSN: 2582 – 7146

Curr. Rese. Agri. Far. (2022) *3*(2), 25-33

Current Research in Agriculture and Farming

Review Article

Peer-Reviewed, Refereed, Open Access Journal

Sustainable Water Management Practices in Agriculture under Climate Change Scenarios: A Review

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Received: 24.02.2022 | Revised: 27.03.2022 | Accepted: 12.04.2022

ABSTRACT

Climate change is intensifying water scarcity, erratic rainfall patterns, and extreme weather events, posing significant challenges to agricultural productivity and global food security. Sustainable water management practices have emerged as essential strategies to enhance water-use efficiency, conserve natural resources, and strengthen the resilience of farming systems. This review highlights recent advances in climate-smart irrigation techniques, rainwater harvesting, precision agriculture, soil moisture conservation, deficit irrigation, wastewater reuse, and integrated watershed management. It also examines the role of digital technologies, remote sensing, and decision-support systems in optimizing water allocation and improving crop performance under changing climatic conditions. Furthermore, the review discusses policy interventions, farmer participation, and institutional frameworks required for effective implementation. Adopting sustainable water management practices is crucial for ensuring resilient agriculture, environmental sustainability, and long-term water security in a changing climate.

Keywords: *Climate change, irrigation efficiency, rainwater harvesting, conservation agriculture, water-use efficiency.*

INTRODUCTION

Water is the single most important production factor in agriculture, and its availability fundamentally determines food security, rural livelihoods and ecosystem health. Globally, irrigated agriculture supplies roughly 40 percent of food from less than 20 percent of the cultivated land and withdraws about 70 percent of all freshwater (FAO, 2020). However, growing populations, urbanisation, dietary transitions and economic development are projected to raise food demand by 50 percent by 2050, while climate change is simultaneously altering the spatial and temporal distribution of precipitation (IPCC, 2014; & Rosegrant et al., 2009).

Cite this article: Kumar, A., Pal, R. K., & Kumar, M. (2026). Sustainable Water Management Practices in Agriculture under Climate Change Scenarios: A Review, *Curr. Rese. Agri. Far. 3*(2), 25-33. doi: http://dx.doi.org/10.18782/2582-7146.325

The Intergovernmental Panel on Climate Change concluded with high confidence that warming, shifting monsoons and more frequent extremes are already affecting crop yields and irrigation reliability across many regions (IPCC, 2014, 2022). Against this backdrop, sustainable water management in agriculture has emerged as a central pillar of climate-smart and resource-efficient farming. Sustainable water management refers to the planning, allocation and use of water in ways that meet present agricultural needs without compromising long-term availability, ecological integrity or social equity (Rockström et al., 2010). It combines technological measures, agronomic practices, infrastructural investments and institutional arrangements to produce more crop per drop while buffering farms against climatic variability.

2. Climate Change Pressures on Agricultural Water Resources

Climate change is altering the agricultural water cycle through several interlinked pathways. Mean global surface temperature has already risen by about 1.1°C above pre-industrial levels, intensifying evapotranspiration and crop water demand (IPCC, 2022). Precipitation regimes are becoming more variable: many semi-arid regions are experiencing declining seasonal rainfall, while monsoonal areas are seeing concentrated, high-intensity events that runoff rather than infiltrate (Trenberth, 2011). Glacier and snowpack retreat in the Himalayas, Andes and Rockies threatens dry-season river flows that feed major irrigation systems (Immerzeel et al., 2010).

Wada et al. (2014) showed that human water consumption already exceeds renewable supply in several major aquifers, including the North China Plain, the Indo-Gangetic Basin and the High Plains of the United States. Climate change is projected to widen this gap by reducing recharge and increasing competition between domestic, industrial and agricultural users. Schewe et al. (2014) estimated that under a high-emissions scenario, an additional 8 percent of the global population could face severe reductions in water resources by 2050. For agriculture, the implications are profound: rising irrigation requirements, declining surface and groundwater reliability, salinisation of coastal aquifers and shifting crop calendars (Elliott et al., 2014).

Figure 1 illustrates the sectoral distribution of global freshwater withdrawals. Agriculture's dominant share underscores why even modest efficiency gains in this sector translate into large absolute water savings. In low- and middle-income countries the share routinely exceeds 80 percent (FAO, 2020), making them especially vulnerable to climatic disruptions of water supply.

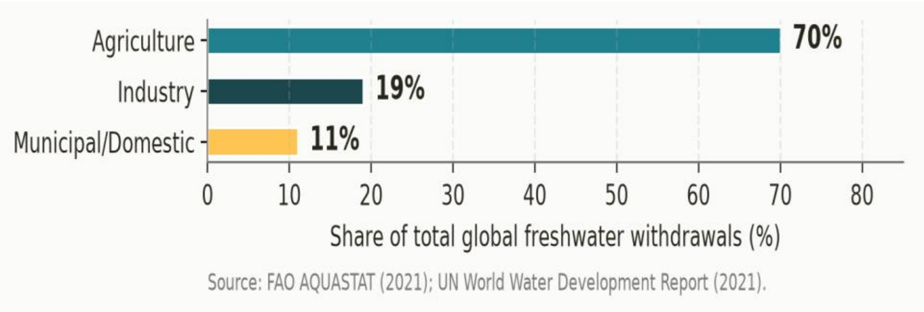

Figure1. Global freshwater withdrawals by sector (≈2018). Adapted from FAO AQUASTAT (2021)

3. Sustainable Water Management Practices

3.1 Efficient Irrigation Systems

Conventional surface irrigation – by furrow, basin or border methods – still accounts for more than 80 percent of the world's irrigated area, with typical field application efficiencies of only 40–60 percent (Howell, 2003; & Narayanamoorthy, 2004). Shifting to pressurised systems offers substantial water savings. Sprinkler irrigation can raise application efficiency to 70–85 percent, while drip and micro-irrigation achieve 80–95 percent because water is delivered directly to the root zone with minimal evaporation and runoff (Brouwer et al., 1989; & Postel, 2000).

Empirical studies confirm large water savings without yield penalty. Narayanamoorthy (2004) showed in field trials in India that drip irrigation reduced water consumption by 40–70 percent and increased yields of sugarcane, cotton and grapes by 20–40 percent compared with surface irrigation. Sivanappan (2006) reported that micro-irrigation expanded crop water productivity in arid and semi-arid Indian states, while van der Kooij et al. (2013) cautioned that gains depend on appropriate design, scheduling and management. Figure 2 summarises efficiency ranges by method.

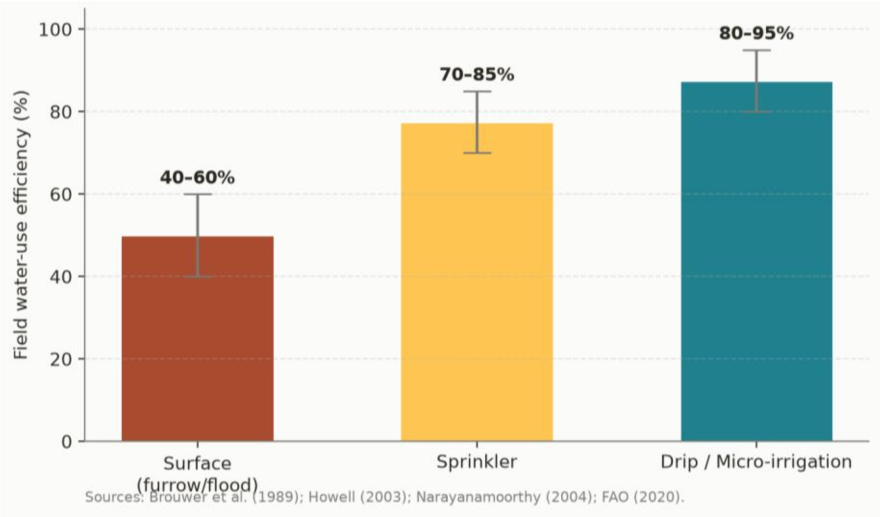

Figure2. Typical water-use efficiency by irrigation method. Compiled from Brouwer et al. (1989), Howell (2003), Narayanamoorthy (2004) and FAO (2020)

3.2 Deficit and Regulated Irrigation

Deficit irrigation deliberately applies less water than the full crop evapotranspiration requirement, targeting stages when plants are relatively tolerant to water stress (Fereres & Soriano, 2007). When designed correctly, this strategy increases water productivity and reduces water demand without proportional yield loss. Geerts and Raes (2009) reviewed deficit-irrigation experiments and concluded that, across diverse crops, the practice consistently raises water-use efficiency, often by 10–30 percent. Partial root-zone drying – wetting only one side of the root system at a time – has shown similar benefits in fruit crops and grapes (Kang & Zhang, 2004).

3.3 Rainwater Harvesting and Water Storage

Rainwater harvesting captures, stores and uses precipitation that would otherwise be lost to runoff or evaporation. It includes on-farm structures such as farm ponds, percolation tanks, check dams and contour bunds, and rooftop systems on rural homesteads. Rockström et al. (2010) demonstrated that supplemental irrigation from harvested water during dry spells doubled cereal yields in rainfed African systems while stabilising production across drought years. Pandey et al. (2003) reported that decentralised rainwater structures recharged shallow aquifers and reduced flood damage in semi-arid India. Watershed-scale rainwater harvesting integrates these elements with vegetation management and is now widely promoted in national policies such as India’s Mahatma Gandhi National Rural Employment Guarantee Scheme.

3.4 Conservation Agriculture and Soil-Moisture Management

Conservation agriculture rests on three principles: minimum mechanical soil disturbance, permanent organic soil cover and diversified crop rotations (FAO, 2017). These practices increase soil organic matter, improve infiltration and reduce evaporative losses.

Hobbs et al. (2008) estimated that no-tillage with residue retention saved 15–50 percent of irrigation water in rice–wheat systems of the Indo-Gangetic Plains. Mulching with crop residues or plastic films, widely adopted in China and parts of the Mediterranean, has been shown to suppress evaporation and increase water productivity by 20–50 percent in maize and wheat (Li et al., 2013). Conservation agriculture also enhances resilience to drought by maintaining surface cover during dry spells.

3.5 Drought-Tolerant Varieties and Crop Diversification

Genetic improvement complements engineering and agronomic measures. Conventional breeding and molecular tools have produced drought-tolerant cultivars of rice, wheat, maize and pulses adapted to water-limited environments (Cattivelli et al., 2008). Reynolds et al. (2009) reported that drought-resilient wheat lines maintained 70–80 percent of their potential yield under moderate water stress, compared with severe losses in susceptible varieties. Diversifying away from highly water-intensive crops such as paddy rice and sugarcane in water-scarce regions, and promoting millets, sorghum and pulses, also reduces agricultural water demand while improving nutritional outcomes (Davis et al., 2018).

3.6 Precision Agriculture and Soil-Moisture Sensors

Digital agriculture is reshaping water management. Soil-moisture sensors, automated weather stations, remote sensing and decision-support tools allow irrigation to be tailored to real-time crop demand. Evett et al. (2020) reported that sensor-based scheduling reduced applied water by 20–40 percent in cotton, corn and forage crops in the United States Great Plains without yield loss. Satellite-derived evapotranspiration products, such as those from the FAO WaPOR portal, enable basin-scale benchmarking of water productivity (FAO, 2020). When linked to mobile advisory services, these tools can democratise access to climate-smart water management for smallholder farmers.

3.7 Treated Wastewater Reuse and Non-Conventional Sources

Where freshwater is scarce, treated wastewater and desalinated water can substitute for conventional sources in agriculture. Globally, about 359 km³ of wastewater is produced each year, of which only a fraction is safely reused (Jones et al., 2021). Israel reuses nearly 90 percent of its treated municipal wastewater for irrigation, and Spain, the United States and Australia have well-developed regulatory frameworks. Properly treated and monitored, wastewater reuse offers a climate-resilient water source while reducing pollution of surface water bodies (WHO, 2006).

3.8 Watershed Management and Aquifer Recharge

Sustainable water management extends beyond the field. Integrated watershed development couples in-situ moisture conservation with vegetative measures, gully plugging and aquifer recharge structures to improve hydrological functioning at landscape scale. Joshi et al. (2008) found that participatory watershed projects in semi-arid India increased cropping intensity by 30–40 percent and improved groundwater levels. Managed aquifer recharge – deliberately diverting surface water to recharge aquifers – is now being mainstreamed in countries such as the Netherlands, India and Australia to buffer against climate variability (Dillon et al., 2019).

4. Trends, Adoption and Quantitative Evidence

The global area equipped for irrigation has expanded steadily, from about 139 million hectares in 1961 to roughly 342 million hectares by 2020 (FAOSTAT, 2022). Asia accounts for over two-thirds of this area, reflecting both monsoonal cropping systems and the prominence of paddy rice (Figure 3). Such expansion has been essential for food security but has also intensified pressure on aquifers and rivers, making efficiency gains imperative.

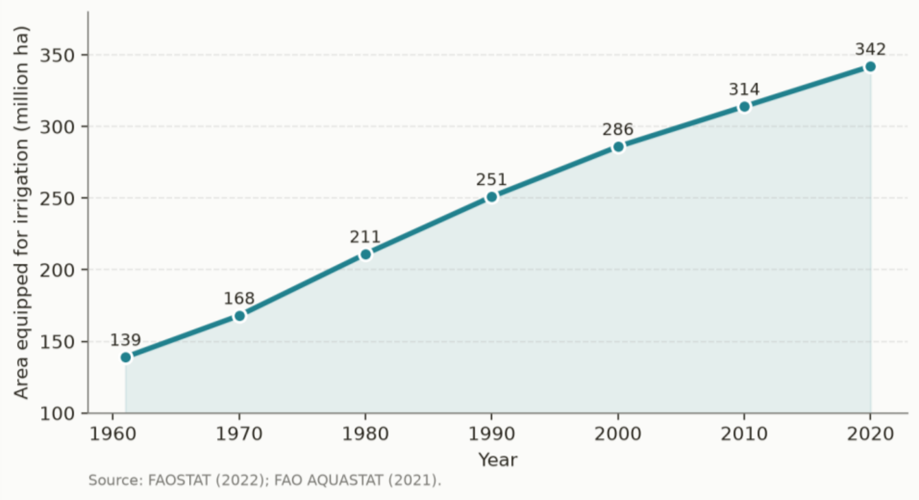

Figure3. Growth of the global area equipped for irrigation, 1961–2020. Source: FAOSTAT (2022)

Despite proven benefits, the diffusion of micro-irrigation remains uneven. By 2017, drip and sprinkler systems covered an estimated 10–12 percent of the world's irrigated area, with the highest penetration in Israel, the United States, Spain and parts of China and India (ICID, 2018). Subsidies and supportive policies, such as India's Pradhan Mantri Krishi Sinchayee Yojana – Per Drop More Crop launched in 2015, have accelerated adoption, but capital cost, fragmented landholdings, unreliable electricity for pumping and limited extension support remain significant barriers (Palanisami et al., 2011).

Adoption of conservation agriculture has grown from less than 50 million hectares globally in the early 2000s to approximately 205 million hectares in 2018–2019, equivalent to about 14 percent of total cropland (Kassam et al., 2019). The Americas and Australia lead, but uptake in Asia and Africa, where small farms predominate, has been slower. Bundled approaches that combine conservation tillage, residue management and improved varieties show the strongest yield-stability gains under drought conditions.

5. An Integrated Framework for Climate-Smart Water Management

No single practice can deliver climate-resilient water management on its own; sustainable outcomes emerge from integrated portfolios that span field, farm and landscape scales (Figure 4). Climate-smart water management combines efficient irrigation, rainwater harvesting, conservation agriculture, crop choice, precision technologies, wastewater reuse, watershed measures and supportive institutions. Rockström et al. (2017) argued that such integration is essential to achieve a doubling of water productivity by 2050, consistent with Sustainable Development Goal 6.4. Importantly, the framework also recognises the social and institutional foundations – farmer participation, water-user associations, equitable pricing and gender-sensitive design – that determine whether technical measures actually translate into impact (Molle et al., 2010).

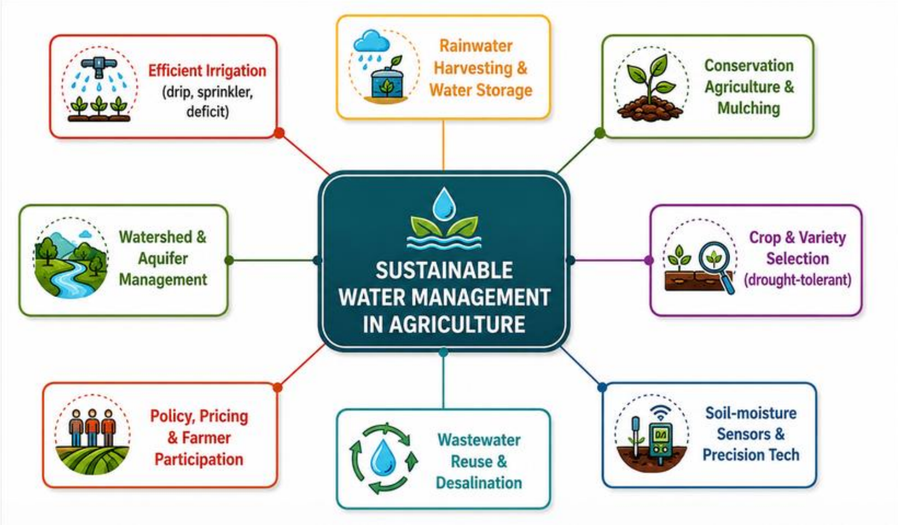

Figure4. Conceptual framework of sustainable water management practices in agriculture under climate change scenarios

6. Challenges and Constraints

Several constraints limit the wider adoption of sustainable water management. First, the upfront capital cost of pressurised systems, sensors and farm-pond construction is prohibitive for many smallholders, particularly in Sub-Saharan Africa and South Asia (Burney et al., 2013). Second, perverse incentives – such as flat-rate electricity tariffs and unmetered groundwater – encourage over-extraction and discourage efficiency investments (Shah, 2009). Third, weak extension services and limited digital literacy hinder uptake of advanced technologies. Fourth, rebound effects can occur: efficiency gains sometimes lead to expansion of irrigated area or shifts to more water-intensive crops, leaving basin-scale withdrawals unchanged or even higher (Grafton et al., 2018). Fifth, climate-change uncertainty itself complicates investment decisions, requiring adaptive and flexible designs.

7. Policy and Future Research Directions

Mainstreaming sustainable water management under climate change requires coordinated policy. Pricing reforms that internalise the true cost of water, coupled with targeted subsidies for the poorest farmers, can align private incentives with public good. Investments in measurement – metering wells, monitoring aquifers and mapping crop water use through remote sensing – are essential to evidence-based governance. Capacity building for extension agents and farmer groups, together with participatory watershed governance, fosters local ownership. Future research should focus on (i) context-specific integration of practices; (ii) low-cost sensors and digital tools tailored to smallholders; (iii) climate-resilient cultivars and cropping systems; (iv) safe reuse of non-conventional water; and (v) gender and equity dimensions of water management.

CONCLUSION

Climate change has elevated water management from a technical concern to a defining challenge for global food security. Evidence reviewed in this paper demonstrates that a wide portfolio of sustainable practices – efficient irrigation, deficit irrigation, rainwater harvesting, conservation agriculture, drought-tolerant varieties, precision technologies, wastewater reuse and watershed measures – can collectively raise water productivity, sustain yields and enhance climate resilience. Quantitative studies up to 2022 indicate that drip irrigation alone can save 40–70 percent of water, conservation tillage 15–50 percent, and integrated rainwater harvesting can double yields in rainfed systems. Yet diffusion of these practices remains incomplete, constrained by economic, institutional and behavioural barriers.

Realising the full potential of sustainable water management requires moving from isolated interventions to integrated, landscape-level approaches that explicitly account for climate-change scenarios. This calls for supportive policies, sustained investment in infrastructure and digital tools, participatory governance and continued research. By coupling proven technologies with sound institutions and farmer agency, agriculture can simultaneously meet rising food demand, conserve scarce water resources and adapt to a changing climate – a triple objective at the heart of sustainable development.

Acknowledgements:
The authors express their sincere gratitude to all co-authors for their cooperation and contributions throughout the study.

Funding:
No funding was received for conducting this research.

Conflict of Interest:
The authors declare that they have no competing interests.

Author Contributions:
All authors contributed to manuscript preparation, critical revision, and final approval.

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