Review Article

Climate Smart Irrigation Practices for Improving Water Productivity in India: A Comprehensive Review

Abstract

India, supporting 17% of the global population, from limited land (2.4% of the world's total) and freshwater resources (4%), faces severe water scarcity issues. The country experiences heightened challenges due to a monsoon climate leading to floods and droughts. Irrigation efficiency in India is 35-40% and irrigated area ~48.9%. To meet the demands of a large or growing population in limited land and water resources, climate-smart irrigation practices (CSIPs) are imperative. These practices not only increase yield but also precisely supply water, reduce water application volume, and enhance soil health under changing climate conditions.Precision water management technologies includes; advanced agro-techniques, micro-irrigation, conservation agriculture, crop diversification, integrated farming systems, and water harvesting. Micro-irrigation, encompassing drip and sprinkler systems, emerges as a critical solution for efficient water use. Techniques like Surface Drip Irrigation and Sub-surface Drip Irrigation (SSDI) not only save water but also enhance nutrient transport and reduce labor costs. The automation of micro-irrigation through sensors and wireless communication revolutionizes traditional practices, ensuring precise water management and boosting agricultural productivity. In addition, advanced agro-techniques, including laser land leveling, furrow-irrigated raised beds, aerobic rice cultivation, system of rice intensification, ground cover cum rice production system and Saguna rice technique have good potential to save water and improve water productivity.Implementing these advanced agro-techniques not only conserves water but also contributes to sustainable agriculture by improving overall water productivity, reducing environmental impact, and enhancing crop productivity. The integration of conservation agriculture (minimum soil disturbance, crop residue cover and crop diversification), integrated farming systems (combine diverse agricultural activities synergistically), and water harvesting is imperative for sustainable water management. This review paper systematically compiles climate-smart irrigation practices, including precision water management, combined with conservation agriculture, crop diversification, integrated farming systems, and water harvesting. This review paper offers researchers a comprehensive understanding of different CSIPs, assessing their impact on water conservation, increased crop and water productivity, and sustainability amid climate change. Farmers can gain practical understandings of CSIPs, while policymakers obtain essential information for addressing national water mission goals.

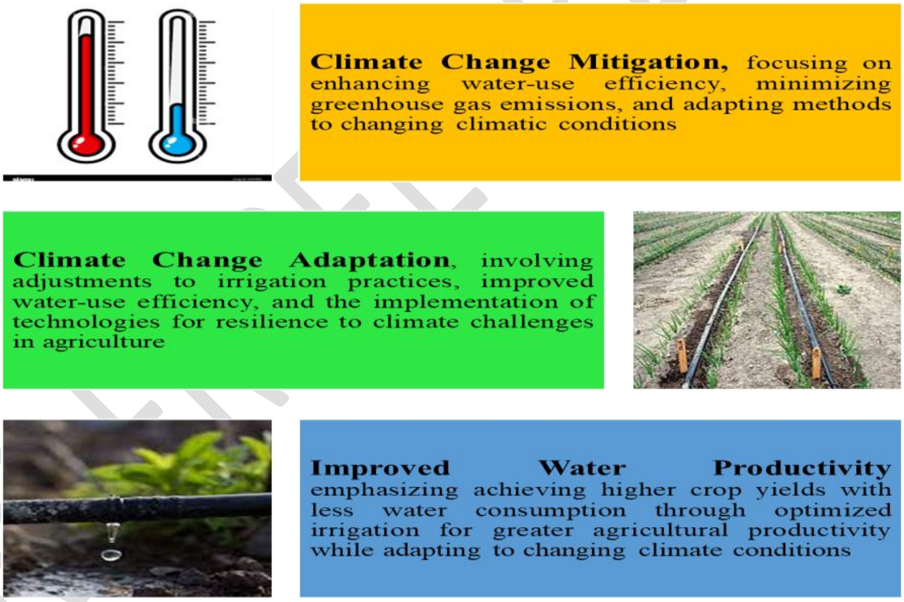
Keywords: automation, climate change, food security, fresh water, micro irrigation, smart irrigation, water productivity

INTRODUCTION

India, representing 17% of the global population, 2.4% of the world's geographical area and 4% of freshwater resources (United Nations,2021). The water availability in India has sharply declined from 3000 m^3/capita/year in 1951 to 1458 m^3/capita/year at present (Lacombe *et al.,* 2019). Agricultural water consumption in South Asia exceeds 90%, with surface water and groundwater contributing 60% and 40%, respectively (Sidhu *et al.*, 2021). Outdated irrigation methods, coupled with climate change challenges, further strain the agricultural landscape (Amarnath *et al.*, 2017). In India, only 48.9% of the net cultivated area, totaling 68.5 Mha out of 140 Mha is irrigated (ASG, 2021). additionally, there is poor irrigation efficiency, standing at only 35-40% (Narayanamoorthy, 2022). Agriculture accounts for 90-98% of total water use, highlighting the need for precision water management technologies (Sidhu *et al.*, 2021). India, produces 20% of global wheat and 31% of rice and irrigated agriculture, constituting 55% of India's overall food production, is crucial for food security (Dhawan, 2017; Sidhu *et al.*, 2021).Groundwater development, supporting 63% of total irrigated land, often relies on subsidies, leading to overexploitation and water table loss (Shah*et al.*, 2019; Sidhu *et al.*, 2021). Faulty irrigation practices and free waterleads to poor irrigation efficiency in India (Shah*et al.*, 2019; Sidhu *et al.*, 2021; Narayanamoorthy, 2022). Climate change impacts, including rising temperatures and rainfall variability, exacerbate water availability issues (Jat *et al.*, 2016; Kaur *et al.*, 2013; Narjary*et al.*, 2014; Yadvinder-Singh *et al.*, 2014). By 2025, over one-third of the global population will face severe water shortages (Kassam *et al.*, 2007). The growing demand for food in water-scarce regions necessitates reallocation, threatening food security. Climate-smart irrigation practices can address this issue (Chaudhry and Garg, 2019; Sidhu *et al.*, 2021.Climate-smart irrigation practices refer to sustainable and adaptive approaches in agricultural water management that consider the impact of climate change (Sikka *et al.*, 2018). These practices aim to enhance water use efficiency, minimize environmental impact, and promote resilience to climate-related challenges (Sikka *et al.*, 2018: Fawzy and Shedeed, 2020). Understanding and implementing appropriate irrigation technologies are essential for addressing water scarcity challenges and optimizing water use efficiency in agricultural practices. Employing technologies like precision irrigation, soil moisture monitoring, and improved irrigation scheduling, climate-smart irrigation seeks to optimize water resources, reduce water wastage, and ensure the sustainable production of crops in the face of changing climate patterns and increased water scarcity (Sikka *et al.*, 2018: Fawzy and Shedeed, 2020: Sidhu *et al.*,2021: Kumar *et al.*, 2023). This review paper systematically compiled the climate smart irrigation practices for improving water use efficiency in India, offering valuable insights for researchers, farmers, and policymakers alike.

Climate Smart Irrigation Practices

Climate-smart irrigation practices refer to sustainable and adaptive approaches in agricultural water management that consider the impact of climate change. These practices aim to enhance water use efficiency, minimize environmental impact, and promote resilience to climate-related challenges (Sikka *et al.*, 2018: Fawzy and Shedeed, 2020).



Climate Change Mitigation, focusing on enhancing water-use efficiency, minimizing greenhouse gas emissions, and adapting methods to changing climatic conditions

Climate Change Adaptation, involving adjustments to irrigation practices, improved water-use efficiency, and the implementation of technologies for resilience to climate challenges in agriculture

Improved Water Productivity emphasizing achieving higher crop yields with less water consumption through optimized irrigation for greater agricultural productivity while adapting to changing climate conditions

Figure1: Principles of Climate Smart Irrigation Practices

CLIMATE SMART IRRIGATION PRACTICES

1. Micro-irrigation

Micro-irrigation includes sprinkler, surface drip, and subsurface drip (Michael, 2009). Sprinkler systems account for 56 percent of total acreage under micro-irrigation, while drip irrigation accounts for 44 percent. Drip irrigation is growing at a faster rate, with a current annual growth rate of 9.85 percent from 2012 to 2015, while sprinkler irrigation has grown at a rate of 6.60 percent during the same time period (Priyan and Panchal, 2017). India's major drip irrigation adopting states are Andhra Pradesh (1.38 Mha), Maharashtra (1.31 Mha), Gujarat (0.80 Mha), Karnataka (0.72 Mha) etc. and country’s total of ~5.96 Mha(ASG, 2021). India's major sprinkler irrigation adopting states are Rajasthan (1.68 Mha), Karnataka (1.04 Mha),Maharashtra (0.56 Mha), Andhra Pradesh (0.51 Mha), Gujarat (0.72 Mha), etc. and country’s total of 6.57 Mha (ASG, 2021).

1.1 Sprinkler irrigation

Sprinkler irrigation technology, an advanced pressured micro-irrigation method mirroring natural rainfall, made its global debut nearly a century ago, gaining widespread application only in recent decades (Michael, 2009). This technique involves the distribution of irrigation water over the crop canopy through an aluminum or high-density polyethylene (HDPE) pipe system. Notably, sprinkler systems minimize water loss in conveyance channels, addressing issues of leaks and seepage (Michael, 2009). They exhibit efficiency even on uneven terrain, ensuring more uniform water dispersion and reducing wastage significantly (Shankar *et al.*, 2015). In contrast to conventional flood irrigation, the adoption of sprinkler systems for cereals and other field crops has yielded substantial irrigation water savings ranging from 30% to 70%. (Kahlown *et al.*, 2007; Li, 2018). The advantages encompass improved water distribution efficiency, reduced water waste, and enhanced agricultural sustainability (Michael, 2009; Evans *et al.*, 2010). As technological advancements continue, the broader implementation of sprinkler irrigation stands poised to contribute significantly to resource-efficient and sustainable agricultural practices globally, addressing water conservation challenges and promoting optimal crop growth (Narayanamoorthy, 2009).

1.2 **Surface drip irrigation**

Surface drip irrigation stands as a sophisticated, low-volume technique meticulously delivering irrigation water (IW) directly to plant roots near the soil surface (Michael, 2009; Al-Shamari and Mahmoud 2020). Operating through a meticulously designed network of pipes, valves, and emitters, this system not only ensures efficient water and nutrient transport but also minimizes soil erosion risks (Michael, 2009). A notable feature of surface drip irrigation is its incorporation of fertigation, a process where fertilizers are seamlessly integrated with irrigation water, curbing nutrient loss through leaching (Michael, 2009). In comparison to traditional flood irrigation methods, numerous studies spanning diverse crops, particularly cereal systems globally (Sidhu *et al.*, 2021; Wang *et al.*, 2013), underscore the water-saving potential of drip irrigation systems, demonstrating savings of up to 50% in cereals like wheat, rice, maize, and various other crops. This emphasizes the role of surface drip irrigation as a sustainable and resource-efficient alternative, contributing significantly to water conservation and agricultural sustainability on a global scale.

1.3 Sub-surface Drip Irrigation (SSDI)

Sub-surface Drip Irrigation (SSDI) emerges as an innovative system that distinguishes itself from surface drip irrigation by minimizing labor costs associated with anchoring laterals during the cropping season, concurrently ensuring the longevity of these laterals. This method not only addresses practical concerns but also delivers substantial benefits in terms of water conservation, nutrient application efficiency, weed control, and overall agricultural management (Lamm, 2002; Umair*et al.*, 2019; Singh *et al.*, 2022). The fundamental principle behind SSDI lies in reducing water loss from the soil surface due to evaporation (Sidhu *et al.*, 2021). By facilitating the direct application of water and nutrients to the crop root zone, SSDI optimizes fertilizer use, curtails weed growth, lowers labor costs, and streamlines cultural operations (Lamm 2002; Camp and Lamm, 2003. The integration of Conservation Agriculture practices further enhances the efficiency of SSDI (Sidhu *et al.*, 2021). CA combines three pivotal interventions: zero tillage, crop rotation, and soil surface cover (mulch). These interventions collectively contribute to improved irrigation efficiency by mitigating evaporation and runoff, simultaneously enhancing soil properties for better water retention and storage in the soil profile (Jat *et al.* 2019; Sidhu *et al.*, 2021). In the Indo-Gangetic plains of India, Jat *et al.* (2019a) conducted studies showcasing the efficiency of SSDI in conjunction with CA. The research revealed water savings of 46.7% and 44.7% in CA-based rice-wheat-mungbean and maize-wheat-mungbean systems, respectively, compared to flood-irrigated CA-based systems. These findings highlight the adaptability of SSDI across different cropping systems and further establish its role in sustainable water management. The broader adoption of SSDI holds immense promise for sustainable agriculture, aligning with global efforts to address water scarcity and promote resource-efficient practices. By mitigating water loss, enhancing nutrient utilization, and minimizing labor inputs, SSDI, especially when integrated with CA practices, emerges as a transformative approach with the potential to revolutionize irrigation strategies and contribute significantly to resilient and sustainable food production systems (Jat *et al.* 2019; Sidhu *et al.*, 2021).

2. Automation in Micro-Irrigation

Automated drip irrigation systems revolutionize traditional agricultural practices, offering precise and efficient water management (Kansara *et al.*, 2015; Rathika*et al.*, 2020; Sidhu *et al.*, 2021). Utilizing technology to monitor soil moisture, climate conditions, and soil types, these systems enable accurate field irrigation. Sensors, microcontrollers, and wireless communication enhance the automation, allowing real-time data analysis for optimized water utilization (Blonquist *et al.*, 2006; El-Marazky*et al.*, 2011; Awati and Patil, 2012). Drip irrigation, in particular, delivers water directly to plant roots, minimizing wastage and conserving resources (Michael, 2009). This innovation addresses water and manpower limitations, providing intelligent, sensor-based solutions for increased yield per drop, reduced water consumption, and improved overall agricultural productivity (Sidhu *et al.*, 2021).

Irrigation treatments	Evapotranspiration (mm)	Water productivity (kg m-³)
2013–2014 growing season		
Automated irrigation system	400.06	1.27
Convention irrigation system	538.25	1.13
2014–2015 growing season		
Automated irrigation system	363.94	1.64
Convention irrigation system	514.31	1.47

Figure2: Effect of automatic drip irrigation for tomato production (Source:Munoz *et al.*, 2003)

2.1 Sensors and methods

Precision irrigation relies on real-time data, requiring sensors to monitor soil moisture, temperature, and meteorological conditions (El-Marazky*et al.*, 2011; Awati and Patil, 2012). Initially, tensiometers and granular matrix sensors were used for soil moisture estimation, later replaced by electromagnetic-based sensors, showing promise for real-timemonitoring (Blonquist *et al.*, 2006). The collected data, converted from analog to digital by microcontrollers, is transmitted using RF modules, Bluetooth, or Wi-Fi to a base station (Kim *et al.*, 2008). Automation involves irrigation controllers activating solenoid valves based on predefined soil moisture thresholds (Nemali and Van Iersel, 2006). Wireless sensor networks (WSNs) enhance automation, exemplified by a drip irrigation system with various sensors like soil moisture, wind speed, and direction sensors, providing increased spatial and sequential resolutions (Joaqu'n*et al.*, 2013). Some systems utilize tensiometers to detect soil metric potential for irrigation scheduling, integrating automated controllers (Montesano *et al.*, 2015). Ongoing research explores variable-rate sensors for improved irrigation efficiency. Early studies (Phene and Howell, 1984; Meron *et al.*, 1995), employed custom-made sensors and data mining techniques for subsurface and drip irrigation automation. Recent advancements, like use of RF modules for remote monitoring, and comprehensive analyses by (Ojha *et al.*,2015; Jain *et al.*, 2016), highlight the role of wireless sensor networks and information and communication technologies in advancing precision agriculture technology.

2.2 Communication techniques

Wireless sensor networks (WSNs)

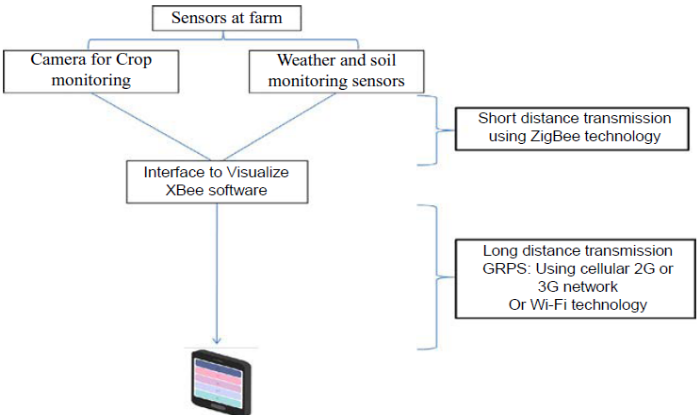


Figure 3 An application of Wi-Fi modules and circuitry design of sensors for automated irrigation. (Source: Sidhu *et al*., 2021)

Wireless Sensor Networks (WSNs) have emerged as a valuable tool for precision agriculture, providing real-time data to enhance productivity and efficiency while mitigating risks associated with climatic anomalies, water shortages, and pests (Akyildiz and Wang, 2005; Wang *et al.*, 2006). Microcontroller advancements and wireless communication technologies, such as Zigbee, Wi-Fi, Bluetooth, RF, and General Packet Radio Service (GPRS), contribute to the development of low-power, low-cost components essential for WSNs (Vergari *et al.*, 2009).

2.3 Internet of Things (IoT) for precision irrigation systems

Anbarasi *et al.* (2019) introduced a smart irrigation system leveraging IoT applications for enhanced agricultural productivity. The system relies on real-time soil data, utilizing a soil moisture sensor to precisely measure soil moisture content (Li, 2012). An operational amplifier controls the pumping motor, automatically turning it on or off based on soil moisture conditions. Through IoT connectivity, farmers can monitor soil moisture status *via* a mobile application or web page, providing information on water sprinkler status. The model includes a sensor hub and a control hub, offering valuable insights for multi-cropping systems. This technology reduces manual efforts for irrigation, improving efficiency and production, particularly beneficial in rural areas with limited rainfall.Sani *et al.* (2019) developed an IoT-based irrigation monitoring and control system employing various sensors and actuators. This smart irrigation system autonomously delivers an appropriate amount of water from a reservoir to crops, demonstrating the potential for efficient and automated irrigation management.

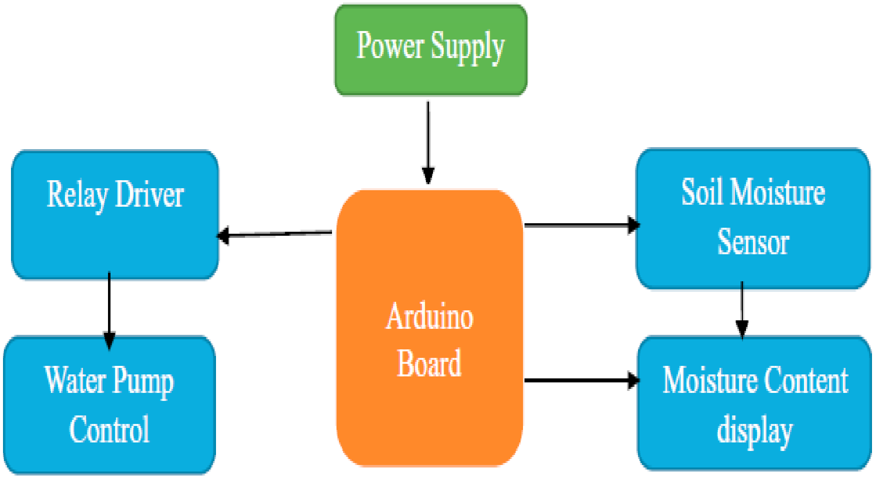


Figure 4IoT-based automation process. (Source: Modified and updated from Jha, K., Doshi, A., Patel, P., 2018).

The system aimed to enhance agricultural productivity by enabling autonomous monitoring and operation of a remote farm. Utilizing a soil moisture sensor, a pump, and a Wi-Fi module, the system collected and transmitted real-time data to a web server. This allowed users to monitor soil moisture levels, ensuring precise irrigation control. The system's flexibility and cost-effectiveness were supported by experimental and simulation results, emphasizing the benefits of remote monitoring and control for irrigation supplies (Gloria *et al.*, 2020).

3. Improved agro-techniques for water saving

3.1 **Laser land leveling**: Laser land leveling, introduced in 2001, alters fields with a gentle slope of 0-0.2%. Utilizing laser-equipped drag buckets, it achieves a smooth land surface within ±2 mm of its average elevation. This precision helps conserve irrigation water by 20-30%, reducing percolation, evaporation, and nitrogen loss. Compared to traditional methods, it saves 6-10% water, covers 3-4% more area, and enhances yields by 5-15%, providing an accurate, graded field for efficient water distribution and improved agricultural outcomes (Jat *et al.*, 2006;2011).

Treatments	Irrigation water use ($m^3 ha^{-1}$)		water productivity (Kg grain m^{-3} water)	
	2002-03	2003-04	2002-03	2003-04
Precision levelling with raised bed planting	2645	2170	1.90	2.39
Traditional levelling with raised beds	3335	2870	1.38	1.65

Precision levelling with flat beds	3525	3060	1.31	1.56
Traditional levelling with flat beds	5270	4309	0.82	1.03
Traditional levelling with flat beds (no fertilizer).	5270	4309	0.51	0.61
CD(p=0.05)	15.87	11.89	0.045	0.040

Table 1: Effect of laser land levelling and planting techniques on water productivity of wheat (Source: Jat *et al.,* 2011)

A study conducted by Jat *et al.* (2011), they found that the precision levelling with raised bed planting exhibited the lowest irrigation water use in both 2002-03 (2645 m^3 ha^{-1}) and 2003-04 (2170 m^3 ha^{-1}), coupled with consistently higher water productivity (1.90 Kg grain m^{-3} water in 2002-03 and 2.39 Kg grain m^{-3} water in 2003-04) (Table 1). This outperformed all other treatments, showcasing its efficiency in resource utilization.

3.2 **Furrow Irrigated Raised Beds**: Furrow Irrigated Raised Beds (FIRBs) involve creating raised beds with three rows. FIRBs facilitate efficient water conveyance and distribution, reducing the time required to reach the lower end from the water source. The method's design minimizes surface area, subsequently reducing water loss through evaporation during irrigation, contributing to improved water use efficiency in agricultural practices (Jat *et al.,* 2011; Das *et al.,* 2014; Pratibha *et al.,*2017; Kumar *et al.*, 2023).

3.3 **Aerobic rice**: This innovative approach was developed through the crossing of high-yielding lowland rice varieties with low-yield upland varieties, resulting in a method that optimizes water usage and enhances overall water efficiency (Prasad, 2011). Aerobic rice cultivation represents a departure from traditional flooded rice fields, employing a water-efficient approach that saves 30-70% of water while achieving high Water Use Efficiency (WUE) (Ghosh, 2003). The key distinction lies in growing rice under non-puddle, non-flooded, and non-saturated soil conditions. The irrigation strategy involves maintaining soil moisture at 0-40 KPa, significantly reducing water losses from seepage, percolation, and evaporation (Prasad, 2004). Irrigation is typically applied carefully, allowing flooding only to reach the soil water content in the root zone up to field capacity (FC). Light irrigation (30 mm) after sowing supports emergence, and subsequent irrigations are guided by the soil water tension at a 20 cm depth, triggering irrigation when it exceeds 20 kPa or when leaves begin to roll. Maintaining optimum soil water conditions around field capacity (30-40 kPa or 0.3-0.4 bar soil moisture potential) throughout growth stages is crucial. Visible signs, such as developing hair cracks on the soil surface or the initiation of tip rolling in the first top leaves, signal the need for irrigation (Prasad, 2004). Applications should be sufficient to bring the topsoil of 20 cm to field capacity (Parthasarathi *et al.*, 2012). Aerobic rice's water management involves a shift from saturated soil moisture regimes, with irrigation scheduled at 5–7-day intervals, supplementing the crop's water requirements. The development and adoption of such techniques contribute to the broader goal of achieving food security while minimizing environmental impact.

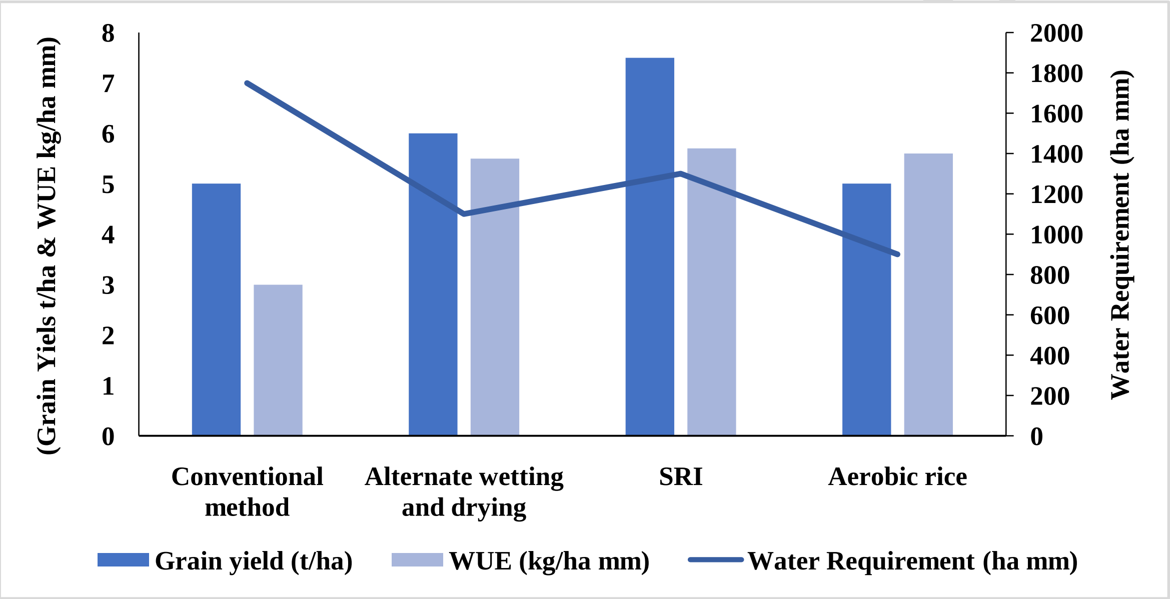
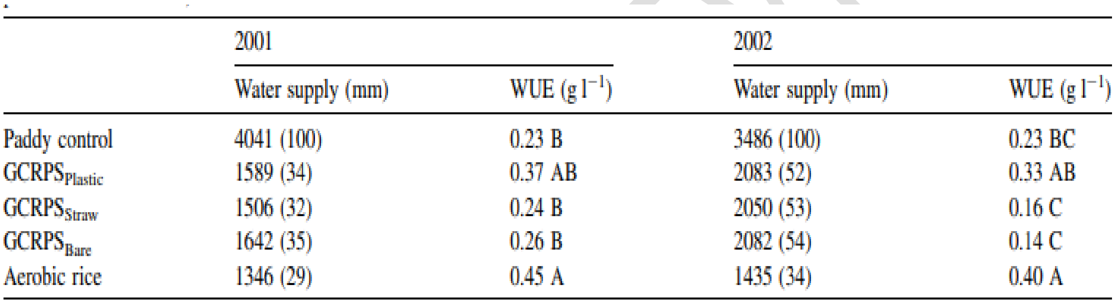


Figure5 : Water Use and Saving in Different Rice Cultivation Systems (Source: Ghosh, 2008)

3.4 **System of Rice Intensification**: The System of Rice Intensification (SRI) revolutionizes traditional rice cultivation (Uphoff, 2006), emphasizing practices that significantly save water (15-30%) and enhance water use efficiency (WUE) to approximately 5.7-5.8 Kg/ha.mm (Ghosh, 2008). Key components include planting young seedlings (8-10 days old) individually with wider spacing (20 cm x 20 cm), optimizing soil moisture during growth stages, and avoiding flood irrigation. SRI minimizes water usage during vegetative growth, introducing only 1-2 cm of water into the paddy, allowing the plot to dry until visible cracks appear (Prasad, 2004). Water savings in SRI are achieved by reducing percolation and implementing alternate wetting and drying instead of continuous flooding (Uphoff, 2006).

3.5 **Direct-Seeded Rice**: Direct-seeded rice (DSR) offers significant water-saving benefits compared to traditional practices like puddled transplanted rice (TPR) (Kumar and Ladha, 2011). The total water savings achieved with DSR, as reported by Saharawat *et al.* (2010), amount to an impressive 35–40% reduction compared to the conventional puddled transplanted rice cultivation. This emphasizes DSR's potential to contribute to sustainable water management in rice cultivation while maintaining or even enhancing yields.

3.6 **Ground Cover Rice Production System**: The Ground Cover Rice Production System (GCRPS) proves beneficial in regions facing limitations in water and temperature for rice cultivation. This innovative technique involves spreading polyethylene on prepared land before sowing. Subsequently, holes are opened on the membrane surface for rice sowing. Using artificial hand dibbling at a 3 cm depth, sufficient seeds are sown on each hill. GCRPS has demonstrated its efficacy by reducing irrigation water consumption while concurrently increasing grain yield and water use efficiency. This method addresses challenges in water-scarce and temperature-constrained environments, showcasing its potential for sustainable rice production (Tao *et al.*,2006; Jin *et al.*, 2016).



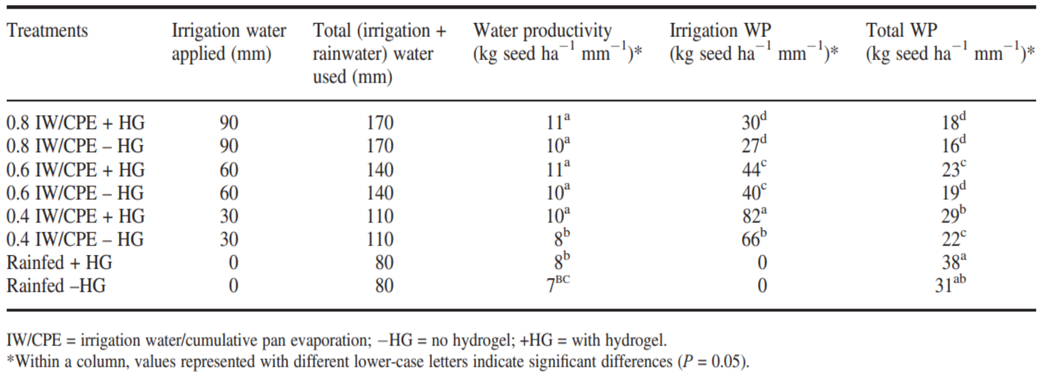
	2001		2002	
	Water supply (mm)	WUE (g l^{-1})	Water supply (mm)	WUE (g l^{-1})
Paddy control	4041 (100)	0.23 B	3486 (100)	0.23 BC
GCRPS$_{Plastic}$	1589 (34)	0.37 AB	2083 (52)	0.33 AB
GCRPS$_{Straw}$	1506 (32)	0.24 B	2050 (53)	0.16 C
GCRPS$_{Bare}$	1642 (35)	0.26 B	2082 (54)	0.14 C
Aerobic rice	1346 (29)	0.45 A	1435 (34)	0.40 A

Table 2: Water supply (irrigation plus rainfall) and agronomic water-use efficiency (WUE, grain yield per amount of water supply, amount of irrigation plus amount of rainfall) of treatments in 2001 and 2002 (Source: Tao *et al.*, 2006)

3.7 **Minimization of Evapotranspiration:**Reducing groundwater depletion involves principles of evaporation control under field conditions. This includes decreasing turbulent water vapor transfer through strategies like growing plants, using windbreaks, and applying straw mulches (Pandey *et al.*, 2017). Soil mulches, achieved by stirring the soil to create a 5-8 cm dry soil layer, effectively reduce evaporation losses by hindering soil moisture rise through capillary action (Reddy and Reddy, 2019). Straw mulches reduce energy absorption and movement above the soil, decreasing evaporation. Chemical mulches, like Hexadecanol, 5cm thick, save water through induced infiltration, reduced evaporation, and weed transpiration reduction (Reddy and Reddy, 2019). For transpiration control(Rana, 2008), which accounts for nearly 99% of plant-absorbed water loss, four principles are applied. These include increasing leaf resistance with antitranspirants like PMA or atrazine, reducing absorbed energy with leaf reflectants like kaolin spray, reducing plant growth with growth retardants, and increasing air resistance with windbreaks (Reddy and Reddy, 2019). Stomatal closing antitranspirants, film-forming antitranspirants like Hexadecanol, and leaf reflectants like kaolin spray are discussed (Das*et al.*, 1979). The success of these methods may vary, and their effectiveness under field conditions is considered. These approaches collectively aim to improve water balance in plants by minimizing evaporation and transpiration losses in agricultural practices.

3.8 **Polymers:** Polymers like hydrogels play a significant role in water-saving practices, particularly in agriculture (Rathore *et al.*, 2019; Rajanna *et al.*, 2022). Hydrogels are superabsorbent polymers capable of retaining large amounts of water, forming a gel-like substance. When incorporated into soil, hydrogels enhance water retention by absorbing and storing water during irrigation or rainfall (Patra *et al.*, 2022). In agriculture, hydrogels act as water reservoirs within the soil, releasing moisture gradually to plant roots (Rajanna *et al.*, 2022). This helps in reducing irrigation frequency and minimizing water wastage. The polymer's ability to retain water also aids in combating drought stress by ensuring a steady water supply to plants (Rathore *et al.*, 2019).

3.9 **Irrigation Scheduling:**Irrigation scheduling is a vital technique that provides essential insights into the correct timing and optimal quantity of water application for crops, thereby maximizing yield and enhancing water use efficiency (Kumar *et al.*, 2021; Gu *et al.*, 2022). Various criteria are employed, including soil water regime methods that calculate soil moisture amounts directly or indirectly through indicators like feel, appearance, DASM, soil moisture tension, climatological approaches, cumulative pan evaporation, and IW/CPE ratio (Majumdar, 2001). Plant indices, such as visual symptoms, critical growth stages, plant population, plant water potential, soil cum sand mini plots, and relative water content, are also considered (Majumdar, 2001).



Treatments	Irrigation water applied (mm)	Total (irrigation + rainwater) water used (mm)	Water productivity (kg seed ha^{-1} mm^{-1})*	Irrigation WP (kg seed ha^{-1} mm^{-1})*	Total WP (kg seed ha^{-1} mm^{-1})*
0.8 IW/CPE + HG	90	170	11^{a}	30^{d}	18^{d}
0.8 IW/CPE – HG	90	170	10^{a}	27^{d}	16^{d}
0.6 IW/CPE + HG	60	140	11^{a}	44^{c}	23^{c}
0.6 IW/CPE – HG	60	140	10^{a}	40^{c}	19^{d}
0.4 IW/CPE + HG	30	110	10^{a}	82^{a}	29^{b}
0.4 IW/CPE – HG	30	110	8^{b}	66^{b}	22^{c}
Rainfed + HG	0	80	8^{b}	0	38^{a}
Rainfed –HG	0	80	7^{BC}	0	31^{ab}

IW/CPE = irrigation water/cumulative pan evaporation; −HG = no hydrogel; +HG = with hydrogel.
*Within a column, values represented with different lower-case letters indicate significant differences ($P = 0.05$).

Table 3: Water use and water productivity of Indian mustard under different micro-sprinkler irrigation schedules and use of hydrogel (Source: Rathore *et al.*, 2019)

3.10 **Conservation Agriculture:** Conservation agriculture (CA) plays a crucial role in water-saving practices by promoting sustainable and efficient use of water resources in farming (Gupta *et al.*, 2002). CA involves three key principles: minimal soil disturbance, permanent soil cover, and diversified crop rotations. By reducing tillage, CA minimizes soil erosion and improves water infiltration, preserving soil structure and moisture and the use of crop residues as cover helps retain soil moisture, reducing evaporation and enhancing water availability for crops(Das *et al.*, 2014; Kumar*et al.*, 2021; Abdallah *et al.*, 2021; Selvakumar and Sivakumar, 2021, Kumar *et al.*, 2022). Additionally, diversified crop rotations, including legumes, contribute to improved soil health and water-use efficiency (Kumar *et al.*, 2021).

3.11 **Crop diversification:** Crop diversification plays a crucial role in water-saving agricultural practices (Yang *et al.*, 2015). By cultivating a variety of crops instead of a single monoculture, farmers can optimize water use and reduce the overall demand on water resources (Qadir *et al.*, 2008). Different crops have varied water requirements and growth patterns, allowing for efficient utilization of available water throughout the year. Crop diversification can involve planting species with diverse root structures and drought tolerance, further enhancing water retention and minimizing losses (Comas *et al.*, 2013). In regions facing water scarcity, crop diversification promotes sustainable water management by mitigating the risk of water-intensive crops dominating the agricultural landscape. Additionally, it helps break pest and disease cycles associated with monocultures, reducing the need for chemical inputs that may contaminate water sources (Lin, 2011; Hussain *et al.*, 2020).

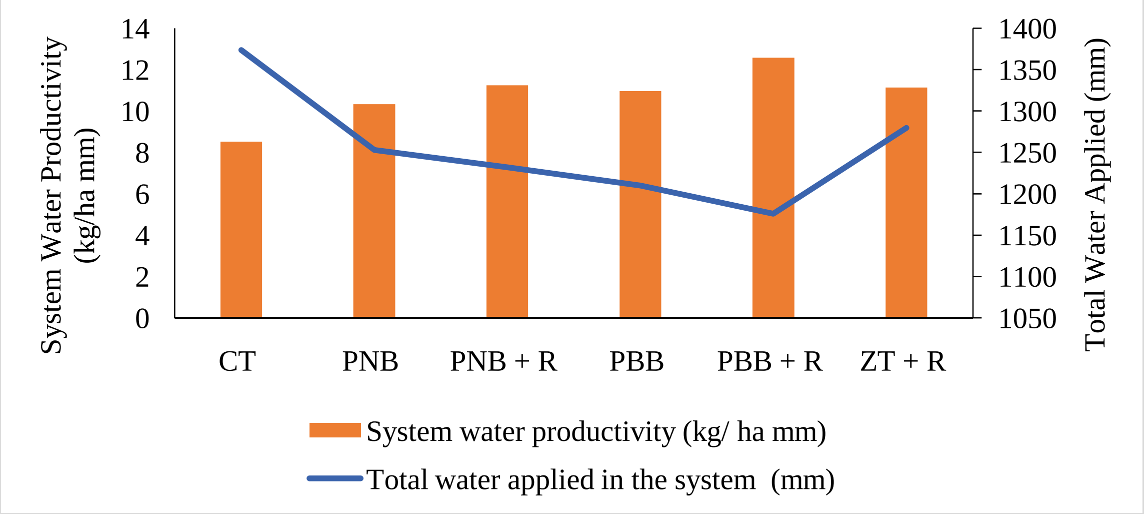


Figure6: Impacts of tillage, bed planting and residue management on water productivity of cotton–wheat system. **CT**: conventional tillage and flat-bed sowing without residue recycling (WRD), **PNB**: zero tilled permanent narrow-bed sowing WRD, **PNB+R**: zero tilled permanent narrow-bed sowing

with residue retention, **PBB**: zero tilled permanent broad-beds owing WRD**, PBB + R**: zero tilled permanent broad-bed sowing with residue retention**, ZT + R**: zero tilled flatbed sowing with-out residue retention (ZT + R) (Source: Das *et al.,* 2014)

3.12 **Integrated Farming Systems**: Integrated Farming Systems (IFS) involves the integration of various agricultural activities such as crop cultivation, animal husbandry, agroforestry, and aquaculture, creating a holistic and sustainable farming approach, play a significant role in water-saving agricultural practices by promoting synergies among different farming components (Behera *et al.*, 2012). IFS involves the integration of various agricultural activities such as crop cultivation, animal husbandry, agroforestry, and aquaculture, creating a holistic and sustainable farming approach. Agroforestry components in IFS contribute to improved water infiltration, reduced runoff, and increased groundwater recharge (Matin, 2006). The diversified nature of integrated systems helps in optimizing water use by cultivating crops that complement each other in terms of water requirements. Furthermore, aquaculture (pond) in IFS can be designed in ways that recycle water and nutrients efficiently, minimizing water wastage (Das *et al.,* 2021). Overall, IFS promotes a more resilient and water-efficient farming system, ensuring sustainable agricultural practices that address water scarcity challenges (Shyam*et al.,* 2023).

3.13 **Water harvesting**: This practice involves collecting and storing rainwater or runoff for later use in agricultural activities (Reddy and Reddy, 2019). By capturing and utilizing rainwater, water harvesting helps reduce dependence on conventional water sources like rivers and groundwater (Gabriels *et al.*, 1998). Water harvesting systems can include storage tanks, ponds, and other infrastructure that allows farmers to harness rainwater efficiently. Various techniques, such as rooftop rainwater harvesting and building check dams, help store rainwater for irrigation purposes (Pradhan and Sahoo, 2019). In agriculture, rainwater harvesting provides an additional water supply during dry periods, reducing the need for excessive groundwater extraction (Reddy and Reddy, 2019). This sustainable approach not only conserves water but also prevents soil erosion and improves groundwater recharge (Sivanappan, 2006). By incorporating water harvesting into agricultural practices, farmers can enhance water-use efficiency, mitigate the impact of droughts, and contribute to sustainable water management in the face of changing climate patterns (Nyamadzawo *et al.,* 2013).

3.14 **Saguna Rice Technique:** The Saguna Rice Technique (SRT) represents a novel approach to rice cultivation, eliminating traditional practices like ploughing, puddling, and transplanting (Bhadsavle, 2019). Important principles include leaving roots and stems for slow rotting, eschewing ploughing and hoeing for weed control, and achieving an earlier harvest by 8 to 10 days. SRT revolutionizes rice farming, mitigating labour-intensive tasks and preventing fertility loss. This method employs permanent raised beds, ensuring optimal moisture conditions and enhanced oxygen supply to the root zone. The SRT iron forma facilitates precise planting distances, promoting an ideal plant population. By avoiding puddling and transplanting, SRT reduces dependence on rainfall timing, offering flexibility in cultivation.

A Case Study on automated drip irrigation in the rice-wheat system

The Borlaug Institute for South Asia (BISA) conducted a comprehensive study on an innovative automated micro-irrigation system within a Conservation Agriculture (CA)-based rice-wheat rotation. The study involved surface drip (SD) and subsurface drip (SSD) irrigation systems and compared them with conventional-till (CT) and zero-till (ZT) flood-irrigated systems. The automated irrigation system utilized a tensiometer with a magnetic switch, triggering the electrically operated tube-well and solenoid valve when the soil metric potential (SMP) fell below critical levels (15 kPa for rice and 35 kPa for wheat). The results demonstrated the superiority of no-till combined with automated drip irrigation, especially in the ZT-SSD configuration, which yielded the highest rice-wheat production. Conversely, conventional tillage with flood irrigation resulted in the lowest yield. Comparing irrigation water productivity, the study revealed a significant improvement under the no-till rice-wheat system with automated subsurface drip irrigation. This approach doubled the irrigation water productivity, showcasing the potential benefits of automated irrigation in enhancing crop yields and water-use efficiency within a CA framework for rice-wheat rotations. The study highlighted the practicality and efficiency of the developed sensor-based, real-time irrigation systems for sustainable and productive agricultural practices.

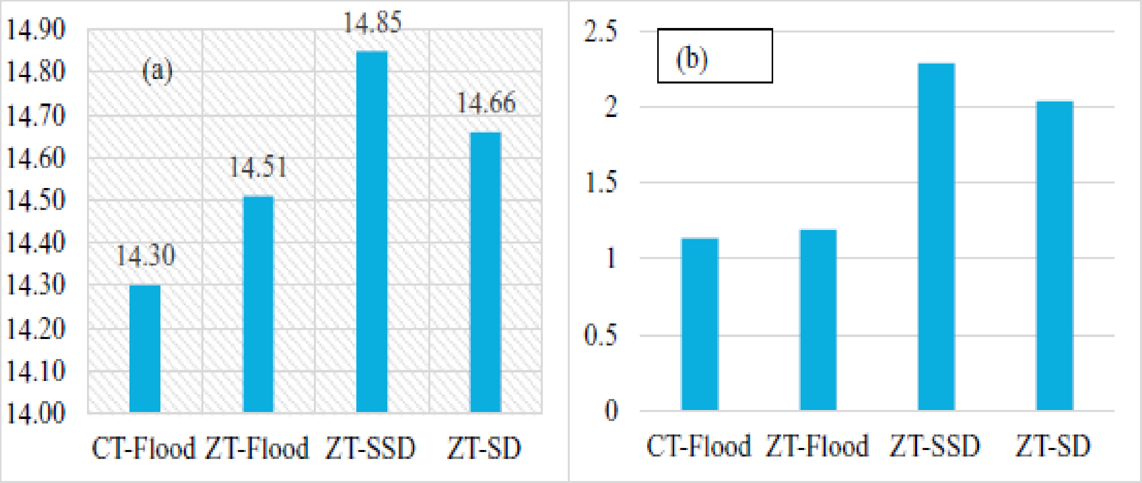


Figure 7: effect of automated irrigation in four management scenarios on (**A**) rice-wheat system yield (tons/ha/year) and (**B**) irrigation water productivity (kg/m^3/year). (Source: Sidhu *et al.*, 2021)

CONCLUSIONS

India, supporting 17% of the global population, from limited land (2.4% of the world's total) and freshwater resources (4%), faces severe water scarcity issues. The country experiences heightened challenges due to a monsoon climate leading to floods and droughts. Irrigation efficiency in India is 35-40% and irrigated area ~48.9%. Precision water management technologies are imperative to improve water production and efficiency. Micro-irrigation, encompassing sprinkler and drip irrigation, is crucial for efficient water use. Sprinkler systems, mirroring natural rainfall, have demonstrated substantial water savings of 30% to 70%. Surface drip irrigation and SSDI integrates with Conservation Agriculture practices for enhanced efficiency. Automation in micro-irrigation, utilizing sensors and wireless communication, revolutionizes traditional practices. Wireless sensor networks with technologies like Zigbee, Wi-Fi, and Bluetooth provide real-time data for precision agriculture. Internet of Thingsapplications further advance precision irrigation systems. Improved agro-techniques for water saving include laser land levelling, furrow-irrigated raised beds, aerobic rice cultivation, SRI, Ground Cover Rice Production System, and minimization of evapotranspiration. Polymers, irrigation scheduling, conservation agriculture, crop diversification, integrated farming systems, and water harvesting contribute to sustainable water management. Precision water management, coupled with climate-smart irrigation practices, can ensure water security, food production, and environmental sustainability in the face of increasing water scarcity and climate change.This review paper offers valuable insights to researchers by comprehensively examining various CSIPs, assessing their impact on water saving, increased crop and water productivity, and sustainability in the face of climate change. Farmers can derive practical insights for informed decision-making, enhancing productivity and resilience. Policymakers gain essential information to design evidence-based strategies, promoting CSIP adoption and addressing water sustainability goals in national agricultural policies.

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