Water Resources Management (2024) 38:3505–3526
https://doi.org/10.1007/s11269-024-03836-6

Improving Water Efficiencies in Rural Agriculture for Sustainability of Water Resources: A Review

Manish Yadav[1] · **B. B. Vashisht**[1] · **S. K. Jalota**[1] · **T. Jyolsna**[1] · **Samar Pal Singh**[2] · **Arun Kumar**[3] · **Amit Kumar**[4] · **Gurjeet Singh**[5,6]

Received: 11 January 2024 / Accepted: 19 March 2024 / Published online: 11 April 2024

Abstract
Water scarcity is an escalating global concern that poses significant challenges to agriculture. The need to feed a growing population, coupled with changing climate patterns, demands a re-evaluation of water use efficiency in major field crops. Water efficiency in agriculture is a critical facet of sustainable water management in rural areas, where agriculture often serves as a primary economic activity. In rural regions, where water resources are often limited, efficient agricultural water management is vital to ensure food security, economic stability, and environmental sustainability. In this review, we have discussed various measures to improve water use efficiency or productivity in agricultural systems. Adopting the strategies for enhancing water productivity at plant and field level may include: rain water harvesting in rural area, soil moisture conservation practices like mulching, crop residue retention and conservation agriculture, better utilization of stored soil moisture by best crop management interventions, irrigation scheduling, integrated farming systems i.e. multiple usage of water in agriculture by combining various farm enterprises like crop production, dairy and fishery. Beside these, reviewed the water use efficiency for important field crops around the world. Review also discussed about how beneficial public policies particularly watershed management in rural area are needed to establish the right socioeconomic conditions for boosting WUE in the agriculture.

Keywords Climate change · Conservation agriculture · Rain water harvesting · Socioeconomic · Water scarcity

1 Introduction

Water is a crucial input affecting the final harvest of agricultural crops (Lamptey 2022). Every form of life, every facet of socio-economic progress, and the preservation of thriving ecosystems all depend on water (Barlow and Clarke 2017). Even good seeds and fertilizers cannot grow to their full potential if plants are not given the right amount of water. Competition for water resources is anticipated to rise due to population expansion, urbanization, and climate change, with an emphasis on agriculture. The world's population will need food

---

Extended author information available on the last page of the article and fibre to fulfil its basic needs by the year 2050, reaching 9.4 to 10.2 billion people, an increase of 22–34% (Boretti and Rosa 2019). The expanding population's demands on water resources are leading to a decline in the quality of the available water supplies, while the need for fresh water for industrial and agricultural expansion is rising quickly. By 2050, it is predicted that agricultural production will need to increase by around 70% due to the rising calorie and complex food consumption that comes along with economic development in developing countries (World Bank 2022). Although there are enough freshwater resources worldwide to support continuing industrial and agricultural expansion, concerns about the long-term sustainable use of water resources are developing (Serageldin 1995). This is especially true when considering the regional differences in the availability and quality of water. Inadequate legislation, severe institutional failures, and financial ripoffs are frequent barriers to enhancing water management in agriculture (Hopken 2022). Water hazards are becoming more prevalent in agriculture which significantly impact productivity. Therefore, improving agricultural water management is crucial for a vibrant and successful agro-food industry (FAO 2017). To ensure just, sustainable, and prosperous rural economies, water is crucial (Massoud et al. 2010). Water is needed for human health, nutrition, and agricultural productivity in addition to providing employment possibilities in several significant fields throughout the rural economy. For rural communities to improve their standard of living, local economies to grow, decent jobs to be created in rural areas and across all economic sectors, and a healthy and productive workforce to be maintained, there must be sustainable water management, adequate water infrastructure, and access to safe, reliable, and affordable water supplies and adequate sanitation services (Qu et al. 2013). Water-related problems might significantly impact rural economies, lives, and suitable employment if they are not addressed. As a recognized human right, access to water that "Entitles *everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses*" (Rights 2000). In recent years, agricultural regions have experienced severe and escalating water restrictions. Farmers in most nations do not pay the full cost of the water they use, which encourages such tendency (Pretty et al. 2001). Irrigated agriculture continues to be the leading user of water globally. 70% of water consumption worldwide and over 40% in several OECD (Organisation for Economic Co-operation and Development) nations is for irrigation in agriculture. Aquifers are depleted and environmental externalities may result from intensive groundwater pumping for irrigation, which has a significant economic impact on the industry and beyond. Therefore, adopting efficient (in terms of water usage) and sustainable water management techniques is imperative (OECD 2022). The current water demand and future projections in different sectors are depicted in Table 1.

1.1 Facts for Global Water Use

The average worldwide freshwater drain from agriculture is 70%. Approximately 67% of global resource extractions are attributed to China, Iran, Pakistan, India, and the United States (Boretti and Rosa 2019). Water demand increased nearly twice as quickly as population growth during the past century. Food production has grown by more than 100% during the past 30 years. By 2050, according to the FAO, an additional 60% more food would be required to feed the world's expanding population (FAO 2017). As a result, water consumption is expected to rise. The available irrigation water is the only half of the total freshwater present globally (Table 2).

Table 1 Water demand and resources: current and projections by 2050

Sector	At present	Global increment by 2050	Reference studies
Global Population	7.9 billion	9.4 to 10.2 billion people	WWAP, 2018; Boretti and Rosa 2019
Water scarce population	1.9 billion (27%)	2.7 to 3.2 billion (42–95%)	WWAP, 2018
Food demand	-	60%	WWAP, 2018
Water use in Agriculture	70%	Uncertain (60% up to 2025)	Alexandratos and Bruinsma 2012
Groundwater withdrawal	800 km^3 per year	1100 km^3 per year	Wada et al. 2016
Water use for industry	20% (75% for energy production and 25% for manufacturing)	Industrial increment 800% in Africa and 250% in Asia; manufacturing will increase by 400% and 85% for energy.	WWAP, 2014; Wada et al. 2016; IEA, 2012
Domestic global water use	10%	300% in Africa and Asia; 200% in Central and South America.	Wada et al. 2016

Table 2 Estimation of storage of freshwater over the globe that available for irrigation in agriculture

Sources	Groundwater	Lakes	Large dam reservoirs	Small dam reservoirs	Total freshwater storage for irrigation	Total freshwater storage*
Total water storage (Bm^3)	22,600,000	182,900	9,025	1,873	2,27,93,798	5,26,67,432
% storage of total freshwater for irrigation	99.1	0.8	<0.1	<0.1	-	-
% storage of total freshwater	49.9	0.34	0.02	0.004	-	-
Reference studies	Gleeson et al. 2012	Messager et al. 2016	ICOLD 2020	Lehner et al. 2011	-	McCartney et al. 2022

*Total freshwater storage includes ice of antarctic, greenland, ground ice sheets, mountain glaciers, wetlands, soil storage and water from paddy fields along with above sources

2 Water Governance, Infrastructure and Settlements for Rural Area

Cities and rural regions compete more for limited water supplies, putting both their prosperity and the environment in danger (Elkind 1998). The water shortage is getting worse as a result of overusing it for irrigation. Groundwater aquifers are being drained and agricultural and non-agricultural water sources are becoming of worse quality. Rural livelihoods frequently depend on a sufficient water supply, and these livelihoods are threatened by growing water shortages and competition for water resources. Therefore, providing access to clean, convenient water sources is crucial. Twenty-two nations are experiencing severe water stress, and over 2 billion people reside in countries with significant levels of water stress. According to estimates, 4 billion people experience acute water stress yearly (UNWWDR, 2019). By 2030, it is predicted that over half of the world's population will reside in regions with significant water stress, leading to population relocation due to rising water demand. However, the increased demand for water in areas with limited availability or high competition for water calls for increased diversification of water sources, such as low-yielding wells and springs, rainwater or storm water harvesting, urban runoff, and wastewater recycling (Alley and Alley 2022). Water scarcity is likely to limit opportunities for economic growth and the creation of decent jobs in rural areas (UNWWDR, 2019). This not only opens up new opportunities for small-scale, intense uses of water, such the growth of extremely lucrative crops in tiny plots, but it also has the potential, via technical advancement, to create jobs in the operation and maintenance of treatment facilities to recover water.

Sixty percent of the world's food is produced on rainfed land, although rainfed cropland is only half as productive as irrigated land for growing crops (ILO 2020) because it immediately lowers farmer's income. An unstable water supply has a detrimental effect on both the quality and quantity of employment in the agro-food industry. Furthermore, the difficulty of relying on rainwater for agricultural output is further exacerbated by the increased unpredictability of rainfall patterns and the increasing frequency of floods and droughts, both of which are influenced by climate change and ultimately leading to reduced yields (Mishra 2017). Flooding, for example, has a disproportionately negative impact on impoverished farmers and indigenous and tribal populations, who are less able to exploit natural resources in an environment of heightened competition, which might speed up the movement of people from rural to urban areas. On the other hand, access to essential water supply and sanitation services might provide extra challenges for migrants, refugees, and internally displaced individuals living in rural regions (Ali 2020). Approaches like the promotion of payments for ecosystem services (PES) help rural communities manage their water resources to compensate for opportunity costs of environmental services and lower poverty to lessen the effect of these difficulties. Despite making up a small portion of all employment, the immediate occupations in the water sector supports many other jobs (Ibok et al. 2014). Thus, rather than creating new jobs, water may be a facilitator of existing ones.

3 Field Water Balance and its Components

The provision of field water has been a key area of agricultural study and management (Molden et al. 2010). Calculation of soil water balance is the popular method for monitoring soil water supply in field condition. Making informed judgments about water management, irrigation scheduling, and water conservation depends on understanding water balances (Sturdy et al. 2008). Water conservation suggests that the available water should be conserved within the area of interest. Calculating the water balance accurately can help correct previous mistakes and prevent them in the future. The water balance elements fluctuate with time, such as from day to day, year to year, etc.

3.1 Concept of Field Water Balance

The field water balance is a record of all the amounts of water introduced to, taken out of, and stored inside a specific volume of soil during a specific period in a specific field (Fries et al. 2020). The rule of conservation of matter, which asserts that matter cannot be generated or destroyed but can only be moved from one condition or place to another, is clearly stated in the water balance. It is a mass balance of the flow and storage of water in surface soil (for a specific depth) on a per-area basis using the hydrologic equation (Ali 2010). There is no appreciable amount of water that is decomposed or composed in the soil, so the water content of a soil profile with a finite volume cannot change without addition from the outside (such as through infiltration or capillary rise), nor can it decrease unless it is transported to the atmosphere by evapotranspiration or to deeper zones by drainage. The two types of boundaries needed for water balance calculations are the physical (or geographical) barrier and the temporal (or time) boundary (Burt, 1999). The methods for estimation of field water balance components and its factor affecting them are given in Table 3. Water balance can be investigated for a field, farm, irrigation district, or hydrological basin. Mathematical formula of field water balance is given by Ali 2010.

$$\mathrm{ET} = \mathrm{P} + \mathrm{I} + \mathrm{G} \pm \mathrm{Q} - \Delta\mathrm{S}$$

Where, ET = Evapotranspiration (mm), P = precipitation (mm), I = irrigation (mm), G = net groundwater flow (mm), Q = run-on or runoff (mm), and ΔS = the change in soil water content within the root zone (mm).

Table 3 Estimation of field water balance components and factor affecting of each component (Wenyan et al. 1994; Ali et al. 2007; Ali 2010)

S.N.	Component	Methods of estimation	Factors
1.	Evapotranspiration (ET)	*Direct method*- Lysimeters *Indirect method*- Empirical equations like FAO Penman- Monteith, Modified Penman etc.	*Weather factor*- temperature, solar radiation, wind-speed, humidity, day-length. *Crop factor*- stomata, LAI, root architecture, cultivar. *Management factors*-weeding, shading, irrigation, mulching, disease and pests, etc. *Soil factor*- Soil moisture retention, soil salinity, hard pan, fertility, etc.
	Evaporation (E)	*Direct method* – Open pan evaporimeter *Indirect method*- Dalton Equation, Penman equation, Mayer formula, Rohwer formula,	Air humidity, temperature, energy, impurities of water, wind speed, available water, soil type, etc.
2.	Surface Runoff	Hydrograph (total runoff and time),	Soil management, topography, cropping rotation, surface cover, crop root zone, depth, rainfall intensity and rainfall distribution, etc.
3.	Deep Percolation or Deep Drainage	*(a) Field-plot water balance* *(b) Drainage lysimeter* *(c) Darcian flux calculation* *(d) Chloride mass balance* *(e) Groundwater table rise* *(f) Tensiometers at lower depths*	Soil structure, Soil texture, pore size, irrigation method, irrigation frequency, stream size, rainfall distribution, opportunity time for infiltration/percolation, hard layer, evaporation demand, groundwater level, hydraulic conductivity, etc.
4.	Capillary Rise from Water-Table	*Empirical equations and by subtraction*	Crop roots, soil texture, depth of water table, rooting depth, irrigation frequency, ET demand, EC of irrigation water
5.	Soil Water Storage	*Gravimetric determination or indirect method viz., neutron moisture meter, time domain reflectometer (TDR), Frequency domain reflectometry (FDR) etc.*	Soil organic matter (SOM), Soil texture, etc.
6.	Rainfall	*Rain gauge*	The air belts, moisture-bearing winds, air temperature, mountain ranges, ocean currents, altitude, inland distance from the coast, etc.
7.	Irrigation	*Parshall flume, weir, flowmeters, venturi meters, throat method, etc.*	Type of soil, method of application, crop water requirement, etc.

4 Estimation of Water Use Efficiency in Agriculture

An important indication of how well plants use their resources is their water use efficiency (Wallace 2000), which affects how the carbon and water cycles adapt to climate change. WUE is the ratio of plant output (or carbon absorption) per unit of water usage. When atmospheric gas exchanges are balanced, plants may absorb more carbon dioxide for photosynthesis and consume less water for transpiration (Ku et al. 1977). Different methods that employ other computations of carbon absorption and water usage can be used to determine the WUE of plants (Gong et al. 2022). While “flux-based” method employs measured exchange of gross primary productivity (GPP) carbon from eddy covariance techniques (Hu et al. 2022), “harvest-based” method uses above-ground biomass (AGB) as an indication of carbon assimilation (De Haan et al. 2021). Depending on the water consumption variables, harvest- and flux-based techniques can be further differentiated. Evapotranspiration, which considers water consumption within an ecosystem, and precipitation, which assumes a connection between water intake and output, can be used in harvest-based techniques. Flux-based WUE techniques can employ either transpiration, which takes into account canopy water consumption, or ET, which indicates ecosystem water use. Flux-based WUE methods heavily rely on plant cover and short-term (daily; half-hourly) weather conditions fluctuations. Briggs and Shantz (1913) first proposed the idea of WUE, which demonstrates a connection between plant productivity and water usage (Fig. 1). The word “WUE” to describe how much biomass a plant produces for every unit of water it uses. Kijne et al. (2003)

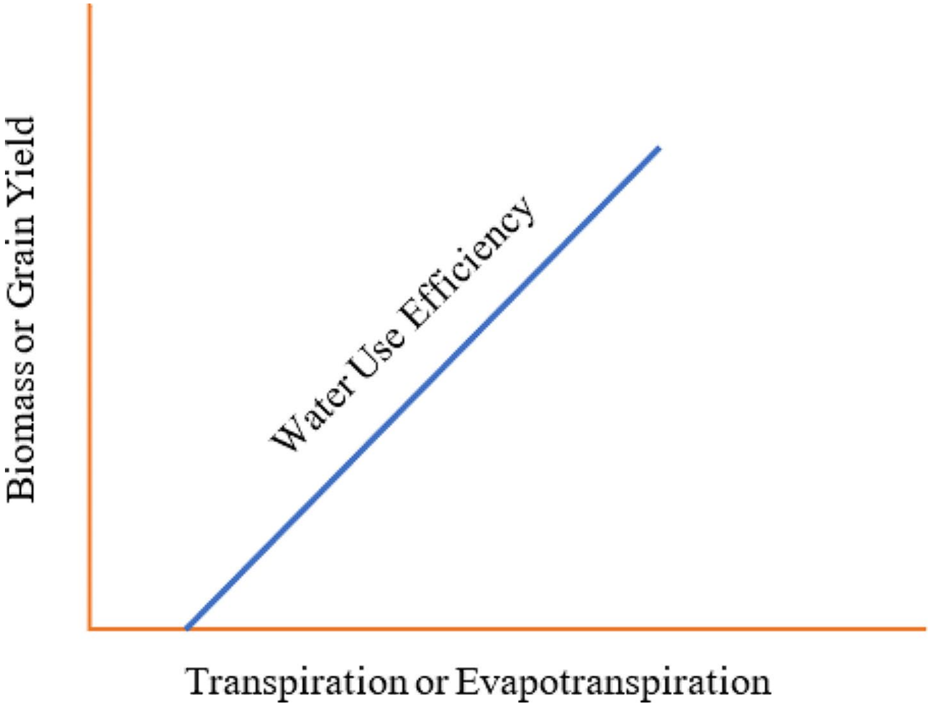

Fig. 1 Relation between water used to yield and water use efficiency

proposed the idea of water productivity as a reliable indicator of an agricultural system's capacity to transform water into food.

The output of a particular design in proportion to the water it uses is how much water it produces, and this may be quantified for the entire system or specific components of it, specified in time and location (Cook et al. 2006).

$$\text{Water productivity} = \frac{\text{Agricultural benefit}}{\text{Water use}}$$

The fluctuation in WUE brought on by climatic circumstances reduces over longer time scales (seasonal, interannual); however, this may not hold true for crops exhibiting abrupt changes in canopy growth during the growing season. In light of these variations caused by changes in plant canopy structure and growth, variation in seasonal WUE at incremental timeframes (i.e., half-hourly) may be significant for agricultural WUE trends (Wang et al. 2022). Environmental factors, which significantly impact rates of both carbon absorption and water usage, also affect the WUE of plants. Environmental factors can influence variables related to carbon assimilation and water utilization to varying degrees (Song et al. 2022). Indeed, climate, soil, vegetation, and hydrological conditions may all have a varied impact on water usage and carbon absorption variables. As a result, changing climatic and hydrological regimes significantly influence agricultural resource use. Other than WUE many indices used for estimation of water use are depicted in the Table 4.

4.1 Measuring Regional and Basin Level Water Productivity

It is relatively difficult to establish water balances for each farm and crop at the large size of an administrative unit, the sub-basin, and the basin. Additionally, a portion of the provided water is frequently reused at the field or system sizes and in other parts of the basin (Playan

Table 4 Water use indices and their formulas (Allen et al. 1998; Gonzalez et al. 2016; Cao et al. 2021)

Indices	Formula	Abbreviations
Water Productivity (WP)	$\mathrm{WP} = \frac{Y}{WF}$	Y- Yield, WF- Total water footprint
Effective utilization degree (WE)	$\mathrm{WE} = \frac{ETc}{WF}$	ET_c – Field crop ET, WF- Total water footprint
	$ETc = Kc \times ETo$	ET_c = Crop Evapotranspiration, K_c = crop coefficient, ET_0 = References ET, (calculated by Penman-Monteith equation)
Water footprint (WF)	$WF = WFA_{blue} + WF_{green} + WF_{green}$	WFA_{blue}= Blue water, WF_{green}= Green water, WF_{grey} = Grey water
Blue water (WFA_{blue})	$WFA_{blue} = Ai \times RIS \times \frac{IWR}{IE}$	WFA_{blue} = Blue water, A_i = Irrigated cropland area, RIS = Relative irrigation supply, IWR = Irrigation water requirement, IE = Irrigation efficiency
Green water (WF_{green})	$WF_{green} = A \times Min \times ETc, Pe$	A = Crop planting area, ET_c = Crop Evapotranspiration, Pe = crop effective precipitation
Grey water (WF_{grey})	$WF_{grey} = \frac{\propto \times AR}{Cmax - Cmin}$	$\propto$ = leaching-runoff fraction AR = rate of chemical application, kg/ha C_{max} = Maximum acceptable concentration C_{max} = Concentration in natural water

and Mateos 2006). The worth of production relative to consumptive use of water by crop is believed to be a better indicator of water productivity to overcome these challenges in capturing the reuse and benefits outside the areas of interest. While in rainfed regions, minimum effective rainfall and evapotranspiration (ET_o), consumptive water usage in irrigated areas indicates the potential ET_o (Molden et al. 2003). Depending on the available data, resources, expertise, and analysis goal, estimates of crop yields and consumptive water use can be made using either statistical data on crop yields, historical values of crop coefficients, and potential evapotranspiration, or more recent approaches utilizing remote-sensing imagery and crop modelling.

4.2 Statistical Approach

Long-term (minimum of three years) subnational data on detailed land use, crop output, number of irrigated and rain-fed areas of various crops, and combined total production can be used to assess the value of crop production. The IWMI Global Climate and Water Atlas (IWMI, 2001), the FAO, and local meteorological offices provide monthly ET_o and rainfall data. These data and crop coefficients for the key crops may be used to calculate consumptive water usage. Amarasinghe et al. (2010) have provided a detailed description of the procedure.

$$\text{Water Productivity (WP)} = \frac{\sum_{\text{jcrops}} \text{Average yield}_{\text{j}}\text{x}\left(\text{Area}_{\text{i}}^{\text{IR}} + \text{Area}_{\text{j}}^{\text{RF}}\right)}{\text{CWU}}$$

where, RF_{jkl} is the effective rainfall of I^{th} month in the k^{th} growth period.

CWU is Crop water use and IR is Irrigation.

5 Water Use Efficiency of Major Field Crops

Unfortunately, WUE remains low in many regions, exacerbated by the reluctance of farmers to adopt efficient water management practices. The current challenges in water use efficiency within major field crops are multifaceted, reflecting a complex interplay of factors that hinder the adoption of sustainable water management practices (Dubois 2011). One primary obstacle stems from the prevalence of traditional irrigation methods that often prove inefficient in delivering water precisely to crops. Outdated practices, such as flood irrigation, contribute to excessive water usage, leading to water wastage, soil erosion, and diminished crop yields. Additionally, the lack of access to modern irrigation technologies and infrastructure in many agricultural regions further hampers efforts to enhance WUE (Hawkesford et al. 2013; Kumar et al. 2023). The WUE of the major crops of India and Mediterranean region are depicted in Tables 5 and 6.

Moreover, the inertia to adopt water-efficient practices among farmers is fueled by a combination of factors, including limited awareness, ingrained habits, and perceived economic risks. Many farmers may not be fully aware of the benefits and long-term gains associated with adopting precision irrigation systems, sensor technologies, and other advanced methods (Keating et al. 2010). Furthermore, the upfront costs associated with transitioning to modern technologies can be a deterrent, especially for smallholder farmers with limited

Table 5 Water use efficiency of major field crops of India

Crops	WUE range (kg m^{-3})	Reference studies
Cereals		
Wheat (23)	0.58–2.25	Singh et al. 2010
Rice (6)	0.30–0.54	
Sorghum (7)	0.56–1.43	
Rabi maize (10)	0.49–1.63	
Pearlmillet (4)	0.41–0.70	
Pulses		
Chickpea	4.45–4.80	Sarkar et al. 2016
Lentil	1.95–3.07	Razzak et al. 2022
Black gram	2.28–3.49	Ray et al. 2023

Table 6 Water use efficiency (kg m^{-3}) for crops of Mediterranean region

Country	Wheat	Corn	Cotton	Soybean	Sunflower	Reference studies
Syria	0.5–2.5	-	0.50–0.74	-	-	Karam et al. 2005; Oweis et al. 2005; Katerji et al. 2006; Katerji et al. 2008
Morocco	0.11–1.15	-		-	-	
Israel	0.6–1.60	-	0.22–0.35	-	-	
Italy	1.02–1.59	0.82–1.80	-	0.47–0.77	0.39–0.72	
Turkey	1.33–1.45	0.22–2.15	-			
France	-	1.6	-	0.55	0.6	

financial resources. This economic aspect exacerbates the resistance to change, creating a barrier to the widespread implementation of water-efficient techniques. Climate change adds another layer of complexity to the challenges faced in achieving optimal WUE (Messina et al. 2022).

Increasingly unpredictable weather patterns, including prolonged droughts and erratic rainfall, disrupt traditional farming calendars and necessitate adaptive strategies. Farmers often resort to compensatory over-irrigation to mitigate the risks associated with climate variability, inadvertently contributing to water inefficiency and environmental degradation (Kalogirou 2001).

6 Measures for Improving Water Use Efficiency in Agriculture

The main users of water are food and agriculture, which need 100 times as much as we need for our own needs (Nijdam et al. 2012). Fresh vegetables and animals are both grown and supported by agricultural water consumption. Agricultural productivity, markets, commerce, and food security are all predicted to be affected by rising water hazards; however, these risks may be reduced with the right legislation. Water use efficiency may also be increased using various techniques, including on-farm water management and irrigation timing (Chaudhry 2018). Using less irrigation lowers the cost of water and labour for the farmer while maximizing the storage of soil moisture (Wu et al. 2022). Growing more food and reaping greater advantages while using less water has recently attracted much interest (Jiang et al. 2022). Many nations and regions are reaching the limits of water shortage within nations (Tian et al. 2021). Boosting water productivity in existing uses of water is the most practical solution for increasing agricultural output in the face of increased water shortages.

6.1 Water Efficient Agricultural Practices in Rural Areas

Water use efficiency can be increased by (i) choose crops and cropping systems based on the availability of water (Verma and Yadav 2018) and (ii) increasing consumptive ET (Prihar et al. 2000) as listed in Fig. 2. Increasing the transpiration (T) increased water use efficiency of plants (Zhou et al. 2020; and Wang et al. 2022). Many water and soil conservation practices followed in rural area to store rain water or to efficient utilization of applied water (Yadav et al. 2022). Based on the physiographic condition and soil properties of area water conservation practices are adopted. In general area of gentle slope contour farming is adopted to conserve soil and water and for area of high rainfall and high slope terracing is help to allow to water to infiltrate into soil and in-situ water conservation (Pratibha et al. 2022).

6.2 Selection of Crop

Based on the water availability of the region selection of crop and variety become crucial for efficient use of water, rainfed area lies water supply only on rainfall so selection of crop should be accordingly (Riaz et al. 2020). Crop may have poor growth and development because only 15 to 30% of total rainfall water is utilizable, the rest of the rain water being lost through runoff, deep percolation and evaporation from soil (Rockstrom et al. 2002). Since more water would be needed for food production than the normal amount of water to produce unit kg of food, the resulting water use efficiency might be very low. In these circumstances, increased fertilizer application often results in an increase in both crop

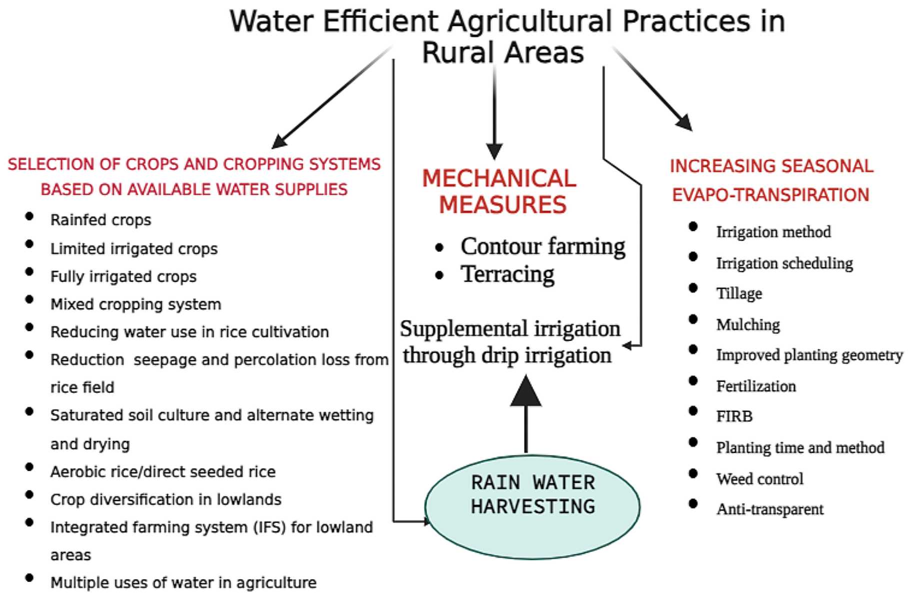

Fig. 2 Efficient practices for water resources utilization in agriculture

production and water use efficiency. Most of the food consumed by underprivileged communities in developing nations is produced through rainfed agriculture (Kakpoet al. 2022). This component accounts for more than 95% of the agricultural land in sub-Saharan Africa, 90% in Latin America, 65% in East Asia, 60% in South Asia, and 75% in the Near East and North Africa (IWMI, 2010). In rainfed farming systems, water productivity, or "the volume of crop produced per drop," is typically low while evaporation losses are considerable (Cantero-Martinez et al. 2007). Land is regularly degraded, crops frequently perish from drought or floods, and there are few mechanisms in place for better water management. Productivity is notably poor in portions of sub-Saharan Africa and South Asia, which causes food insecurity and poverty for rural communities.

6.3 Selection of Cropping System

Rainfall amount and intensity, topography, the ability of the soil to retain water and infiltrate it, the depth of the root zone, and soil depth all affect how much of the precipitation is transformed into soil water that is useful to plants (Assouline 2013). The sort of cropping system that can be used in a location is determined by the depth of the soil because of its impact on the water storage capacity that is available (Milly 1994). Only monocropping of corn or sorghum is possible in the shallow black soil of Madhya Pradesh region with 10 cm of available water. While double cropping can be done on deep soil with 200 mm of available soil moisture, monocropping or intercropping can be done on medium soil depth (Singh et al. 2010). The ability of the crops to adapt to the current climatic and soil conditions, rather than the amount of water, limits the crops that can be grown under these circumstances. Generally speaking, C_4 plants have the ability to consume less water than C_3 plants, especially in semiarid environments (Lara et al. 2011). Under the limited water availability conditions, selection of crop should equally important to irrigation scheduling (Chai et al. 2016).

6.4 Crop Rotation and Mixed Cropping

Crop rotation diversification would boost the entire cropping system's resilience as a means of adapting to climate change. In order to ascertain whether including diverse rotation of wheat and barley will boost water use efficiency. Alvaro-Fuentes et al. (2009) studied 4 rotations in NE Spain. When compared to monoculture systems, the WUE of the total rotation system was lower when rapeseed and vetch not been able to achieve a produce in a number of the years. When grown in an intercropping system, peanut showed a greater WUE from 0.00015 kg plant^{-1} mm^{-1} when grown in monoculture to 0.00022 kg plant^{-1} mm^{-1}. They claimed that the intercropping technique would provide benefits for more effective water use in settings with restricted water supplies (Franco et al. 2018).

6.5 Crop Residue Incorporation

In addition to enhancing the physical, chemical, biological, and biological (e.g., biodiversity, earthworm) properties of soils, soil organic matter (SOM) also reduces climate change by storing carbon in soils (Page et al. 2020). All of these advancements result in better soil water use for growing crops. Currently, up to 25–75% of the SOC in agricultural soils around the globe may liable to lost as a result of intensive farming methods, and roughly 45% of soils in Europe have low organic matter levels (Zahoor et al. 2019). Around 511 Mt of crop wastes are produced worldwide (Venkatesh et al. 2022). Crop leftovers can be used as a sustainable and cost-efficient management approach to maintain agricultural soil fertility, SOC levels, and ecosystem services.

6.6 Rainwater Harvesting

We only rely on rivers, lakes, and groundwater to meet our needs for water (Zhang et al. 2022). The ultimate source that supplies all of these sources, though, is rain. Making the best use of rainfall where it falls, or conserving it so that it doesn't flow away and cause flooding elsewhere, is known as rainwater harvesting (RWH) (Zahoor et al. 2019). When necessary, the augmented resources can be extracted (Abdulla and Al-Shareef 2009). The maximization of benefits of RWH (Gee et al. 2022) helps to the increase the water use efficiency in rural areas.

6.7 Conservation Tillage

Existing tactics, such as conservation tillage, can assist farmers in reducing the risks brought on by climate change and variability while also increasing the effectiveness of resource utilization. Conservation tillage is described as a strategy that leaves at least 30% of the soil surface covered with agricultural residues from cover crops or cash crops after planting (USDA, NRCS). The minimum level of soil cover determined by research to be required to prevent severe soil loss is 30%, but higher residue amounts are recommended (Zahoor et al. 2019). Conservation tillage, in conjunction with cover crops, has the ability to minimise subsurface compaction, minimize erosion, and improve soil organic carbon (SOC) build-up, all of which have a positive impact on a variety of soil physical and chemical properties (Kaurin, 2018). Normally, puddled transplanted rice required 35 to 40% more irrigation water than zero tilled direct seeded rice (Bhushan et al. 2007). Conservation agriculture required 41–43% less water compared to conventional tillage (Rashid 2005). Transplanted rice in bed as compared to the conventional tillage saves 37% irrigation water without sacrificing grain yield during the dry season (Rahman and Islam 2008).

6.8 Irrigation Scheduling

In most developing countries as well as many arid places, increasing irrigation efficiency is becoming a major concern (Mubeen et al. 2016). Conventional irrigation scheduling has sought to maintain soil moisture levels near the field's carrying capacity while supplying an adequate water supply for higher water productivity. A number of unique approaches to irrigation scheduling, however, have been developed recently but have not yet been widely embraced. Instead of directly sensing the soil moisture condition, many of these rely on the plant's response to water shortages. (Erdem, 2010). The objectives of the irrigator and the irrigation system at hand play a significant role in the type of irrigation scheduling that is selected. In general, more complex scheduling techniques call for more precise application systems (Chebil and Frija 2016). The average increased in water use efficiency due to deficit irrigation was 9.3% and 6.4% for wheat and maize, respectively (Li et al. 2022).

6.9 Moisture Conservation Practices

Moisture conservation techniques are used to increase yield in water-scarce areas (Datta et al. 2022). Li et al. (2018) compared the effects of plastic and straw mulch on potato WUE and discovered that straw mulch enhanced production by 16% while plastic mulch raised it by 24%. This led to a 29% increase in potato water use efficiency under a plastic mulch and a 6% increase under a straw mulch. According to Liu et al. (2014), different types of mulch had no effect on water use efficiency, but plastic mulch boosted water use efficiency when compared to no mulch, and the extra water conserved as a result of the decreased soil water evaporation could support higher plant stand. Zhang et al. (2017) conducted a review of the impacts of mulch on water use efficiency and found that overall, mulch raised water use efficiency by 61% as a result of the altered water balance and the more productive maize crop. In semi-arid areas, crop residue applied to the soil surface has demonstrated benefits in reducing soil water evaporation and boosting water use efficiency (Hatfield et al. 2019). Soil management techniques revealed that adding wheat residue at a rate of 5 t ha1 along with a 350 mm irrigation boosted soil water availability and increased grain yield by 62% and WUE by 35% (Ali et al. 2018). A more efficient production method in water-limited conditions would be made possible by the planting pattern and irrigation on wheat in the North China Plain. (Wang et al. 2014).

6.10 Supplemental Irrigation

When using this type of managed deficit irrigation as opposed to simply rain-fed agriculture, the timing and use of scarce water supplies can have a highly positive impact. (Zhang and Oweis, 1999; Solomon and Labuschagne 2003 and Evans et al. 2008). Supplemental irrigation reduces drought vulnerability and enables farmers to make the use of scarce resources by working in tandem with in-situ water harvesting techniques like mulch or bunds. Therefore, one of the most important steps in increasing yields and water productivity in rainfed areas is to mitigate the consequences of short-term drought (Rao et al. 2016).

6.11 Integrated Farming System in Rural Areas

In lowland ecosystem, water use efficiency can be enhanced inclusion of fisheries in the system. Along the rice cultivation (0.46 kg m^{-3}) and in the same amount of water increased the water productivity many folds by introducing fishery (3.08 kg m^{-3}) (Palanisami and Ramesh 2009). The combination of other farm enterprises like crop with fish production, crop along with dairy, etc. gives more revenue per unit quantity of water. When allied enterprises and crops were involved, water productivity improved significantly. Dairy production among the allied industries uses the least amount of water, producing the highest water productivity (Singh et al. 2010).

7 Watershed Management in Rural Area

The Watershed theory planners may coordinate the use of water, soil and plants in such a way that conserves natural resources and maximizes their production by using the watershed method (Carrier 2022). The watershed is the proper hydrological unit for technical efforts to manage water and soil resources for production and conservation (Gashaw 2015). However, watershed management is more challenging because watersheds seldom ever coincide with limits established by humans (Table 7). The primary social issue with watershed development is that benefits and costs are frequently distributed inequitably, which increases the likelihood of disagreement and conflict. Most of the time, watershed projects have an unequal cost and benefit distribution, with costs disproportionately borne upstream, typically by the poorer farmers, and benefits disproportionately realized downstream, where water use is concentrated and richer farmers own the majority of the land. Internalizing costs and benefits in a way that includes all stakeholders in a win-win situation is difficult (Aglanu 2014).

7.1 Water Rights in Watershed Development

The results of resource governance are essentially shaped by property rights and organizations for collective action (Sharma et al. 2005). The majority of effective watershed development initiatives either add to or generate new surface water bodies. It is difficult to divide up the produced resources and ensure their sustainability, especially the groundwater supply. Everyone in the hamlet, even landless labours and small farmers, received advantages equally in the renowned Sukhomajri watershed, creating an incentive for everyone to save water. While surface water resources may be somewhat controlled by conveyance, managing groundwater resources is more challenging (Jakeman et al. 2016). The availability of water recharged by an effort in one village may not always be the case in small watersheds for the same population (Kerr 2002). Water laws in many nations, including India, expressly declare that every landowner has the right to pumping water from under his land as long as it does not impede the availability of drinking water. Therefore, project groups can attempt to negotiate groundwater sharing agreements but cannot complete landowners who disagree to comply. There have been multiple cases where the community lost out on the benefits of improved groundwater supplies possible by investment and a small number of wealthy or

Table 7 Watersheds and management focus relevance to hydrology (Darghouth et al. 2008; Chandrakar et al. 2016; www.worldbank.org/water)

Type of watershed	Influence of land use on hydrology	Typical management focus
Micro-watershed	Very strong	Participatory planning: BMPs; site design
Sub-watershed	Very strong to strong	Stream classification; land use planning /zoning land, water resources and stakeholders' management
Watershed	Strong to moderate	Watershed-based zoning; land use and water resources planning; stakeholder management; policy norms, regulations and incentives
Sub-basin	Moderate to weak	Basin planning; stakeholder management policy, legal framework and incentives
Basin	Weak to very weak	Basin planning; stakeholder management policy, legal framework and stakeholders incentives

important farmers for their own use or even sale to the neighbouring farms (Rosenzweig and Binswanger 1992).

7.2 Managing Rainwater for Improved Livelihoods

Around 60% of the world's food output comes from the 80% of the agricultural area that receives rain (Oweis and Hachum 2009). Farmers in these areas cannot make significant investments in rainfed agriculture due to the unpredictable nature of the weather and their precarious socioeconomic situation. It is feasible to increase production through enhanced rain WUE in rainfed regions by using a comprehensive and collaborative consortium strategy (Wani et al. 2003). A road map for better livelihoods is provided by the convergence of watershed activities such as agriculture, horticulture, livestock, fisheries, poultry, and microenterprises to add value to rural produce (Table 8). Numerous bright spots have been developed under various agro-ecologies as a result of in-situ and ex-situ rainwater conservation using various cutting-edge methods and improving rainwater-use efficiency through supplementary irrigation. Additionally, there is a need to look into and research various alternatives to support micro businesses at the village level and paths for market connections for rural commodities (Haggblade et al. 2007).

7.3 Integrating Watershed Management Institutions

Watersheds are natural physical units, but through time, institutions crucial to their management have developed that do not precisely adhere to their physical limits. These institutions interact in various action contexts to support or restrain those who manage watersheds. Again, various elements (physical, social, and cultural) impact the arena, but institutions are a unifying component and a key motivator for decision-making (Young 1999). Agents engage with one another when making judgments inside and between several venues, and institutions integrate with many complicated ways to support and limit judgments. It will be easier to appreciate the intricacy and interconnections of institutions in different fields if you are aware of the institutions involved. Various factors affect resource management in watershed, yet the institutional solutions offered are frequently out of step with the actual situation (Tallis and Polasky 2009). By establishing new institutions, external organizations (NGOs, donors and state governments) impose various conceptions and requirements (carried through money). Rarely do these financial organizations try to analyze and fix the institutional flaws in the current distributive governance system. The process progressively excludes the poor who are trapped between the macro (formal) and micro (informal). To solve them, numerous institutions must effectively resolve issues like education, a lack of possibilities for earning money, overcoming natural limitations, and, most crucially, societal pressures that have frequently contributed to their poverty (Migdal 2015).

Table 8 Impact of watershed management practice on production and productivity

Watershed	Reduction in soil loss (%)	Increased production area (%)	Crop production and productivity increment (%)	Reference studies
Gereb Shilina	50	5	5–20	Gebregziabher 2012; Gashaw 2015
Goha Cheri	75	5–20	20–50	
Bedesa Kela	35	5–20	5–20	

8 Conclusions

Improving water allocation and efficiency is crucial for meeting current food demand and ensuring future growth. Water usage efficiency is essential for the sustainability of rural communities worldwide. This can be achieved by increasing agricultural water productivity, reducing water outflows, improving soil and water management techniques, increasing soil water storage, and redistributing water from low to high priority uses. Advanced irrigation techniques and the integration of fisheries, dairy operations, and other businesses can further enhance productivity and water use efficiency in agriculture. Positive public policy is needed to establish a favorable socio-economic environment. Soil moisture conservation practices, rainwater harvesting, and the use of anti-transparent materials can help reduce crop ET demands and enhance crop yield efficiency. Integrated farming systems are sustainable approaches to efficient water use in rural areas, generating income for farmers throughout the year. Watershed management in rural areas helps to establish the right socio-economic conditions and boost the WUE in the agriculture.

The review paper calls for a holistic and integrated approach to address water scarcity in rural agriculture. It highlights the significance of adopting sustainable water management practices, technological interventions, and supportive policies to ensure the long-term sustainability of water resources, thereby securing the future of agriculture and rural livelihoods.

Acknowledgements Authors are thankful to CA Ganesh Yadav for his constant support.

Author Contributions Conceptualization and methodology: M.Y. B.B.V and S.K.J.; validation, formal analysis: A.K. and A.K.; writing-original draft: M.Y. and J.T.; writing-review and supervision: G.S. and S.P.S. All authors have read and agreed to the publish the manuscript.

Funding This work has not received any funding.

Data Availability Not applicable. No datasets were generated or analyzed during the current study.

Declarations

Ethical Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Competing Interests The authors have no relevant financial or non-financial interests to disclose.

References

Abdulla FA, Al-Shareef AW (2009) Roof rainwater harvesting systems for household water supply in Jordan. Desalination 243(1):195. https://doi.org/10.1016/j.desal.2008.05.013

Aglanu LM (2014) Watersheds and rehabilitations measures-a review. Resour Environ 4(2):104–114

Alexandratos N, Bruinsma J (2012) World agriculture towards 2030/2050: the 2012 revision. ESA Working paper No. 12−03. Rome, Food and Agriculture Organization of the United Nations (FAO)

Ali MH (2010) Fundamentals of irrigation and on-farm water management: volume 1. Springer, New York, pp 331–372

Ali AH (2020) Analyzing the causes and challenges related to internal displacement in Somalia: the case of IDP camps in Daynile and Kaxda Mogadishu from 1990 to 2020. Dissertation, United States International University-Africa

Ali MH, Hoque MR, Hassan AA, Khair MA (2007) Effects of deficit irrigation on wheat yield, water productivity and economic return. Agric Water Manag 92:151–161

Ali S, Manzoor AJ, Sohail A, Khan A, Khan MI, Khan MI et al (2018) Soil amendments strategies to improve water-use efficiency and productivity of maize under different irrigation conditions. Agric Water Manag 210:88–95. https://doi.org/10.1016/j.agwat.2018.08.009

Allen RG, Pereira LS, Raes D (1998) Crop evapotranspiration: guidelines for computing crop water requirements, irrigation and drainage. FAO Irrigation and Drainage, Rome

Alley WM, Alley R (2022) The water recycling revolution: tapping into the future. Rowman & Littlefield

Alvaro-Fuentes J, Lampurlanes J, Cantero-Martínez C (2009) Alternative crop rotations under Mediterranean no-tillage conditions: biomass, grain yield, and water-use efficiency. Agron J 101(5):1227–1233. https://doi.org/10.2134/agronj2009.0077

Amarasinghe U, Malik RPS, Sharma BR (2010) Overcoming growing water scarcity: exploring potential improvements in water productivity in India. Nat Resour Forum 34:188–199. https://doi.org/10.1111/j.1477-8947.2010.01305.x

Assouline S (2013) Infiltration into soils: conceptual approaches and solutions. Water Resour Res 49(4):1755–1772. https://doi.org/10.1002/wrcr.20155

Barlow M, Clarke T (2017) Blue gold: the battle against corporate theft of the world's water. Routledge. https://doi.org/10.4324/9781315096216

Bhushan L, Ladha JK, Gupta RK, Singh S, Tirol-Padre A, Saharawat YS et al (2007) Saving of water and labor in a rice–wheat system with no-tillage and direct seeding technologies. Agron J 99(5):1288–1296. https://doi.org/10.2134/agronj2006.0227

Boretti A, Rosa L (2019) Reassessing the projections of the world wate development report. NPJ Clean Water 2(1):1–6. https://doi.org/10.1038/s41545-019-0039-9

Briggs LJ, Shantz HL (1913) The water requirement of plants. US Department of Agriculture, Washington, DC, pp 282–285

Burt CM (1999) Irrigation water balance fundamentals. In Conference on Benchmarking Irrigation System Performance Using Water Measurement and Water Balances in San Luis Obispo, CA

Cantero-Martinez C, Angás P, Lampurlanes J (2007) Long-term yield and water use efficiency under various tillage systems in Mediterranean rainfed conditions. Ann Appl Biol 150(3):293–305. https://doi.org/10.1111/j.1744-7348.2007.00142.x

Cao X, Xiao J, Wu M, Zeng W, Huang X (2021) Agricultural water use efficiency and driving force assessment to improve regional productivity and effectiveness. Water Resour Manag 35(8):2519–2535. https://doi.org/10.1007/s11269-021-02845-z

Carrier MB (2022) An examination of Watershed planning and headwaters bioregionalism: the case of the Oak Ridges Moraine, Ontario. Dissertation, Queen's University Canada

Chai Q, Gan Y, Zhao C, Xu HL, Waskom RM, Niu Y, Siddique KH (2016) Regulated deficit irrigation for crop production under drought stress. A review. Agron Sustain Dev 36(1):1–21. https://doi.org/10.1007/s13593-015-0338-6

Chandrakar B, Dewangan NP, Verma S, Mishra A (2016) Empowering community for river basin management. In Urban Hydrology, Watershed Management and Socio-Economic Aspects. pp 323–329

Chaudhry AM (2018) Improving on-farm water use efficiency: role of collective action in irrigation management. Water Resour Econ 22:4–18. https://doi.org/10.1016/j.wre.2017.06.001

Chebil A, Frija A (2016) Impact of improving water-use efficiency on its valuation: the case of irrigated wheat production in Tunisia. Afr J Agric Resour Econ 11(2):131–140. https://doi.org/10.22004/ag.econ.241860

Cook S, Gichuki F, Turral H (2006) Water productivity: estimation at plot, farm, and basin scale. Basin Focal Project Working Paper No. 2. Challenge Program on Water and Food, Colombo

Darghouth S, Ward C, Gambarelli G, Styger E, Roux J (2008) Watershed management approaches, policies, and operations: lessons for scaling up

Datta D, Chandra S, Nath CP, Kar G, Ghosh S, Chaturvedi S (2022) Soil-plant water dynamics, yield, quality and profitability of spring sweet corn under variable irrigation scheduling, crop establishment and moisture conservation practices. Field Crops Res 279:108450. https://doi.org/10.1016/j.fcr.2022.108450

De Haan K, Khomik M, Green A, Helgason W, Macrae ML, Kompanizare M, Petrone RM (2021) Assessment of different water use efficiency calculations for dominant forage crops in the Great Lakes Basin. Agric 11(8):739. https://doi.org/10.3390/agriculture11080739

Dubois O (2011) The state of the world's land and water resources for food and agriculture: managing systems at risk. Earthscan

Elkind SS (1998) Bay cities and water politics: the battle for resources in Boston and Oakland. Development of Western Resourc

Erdem Y, Arin L, Erdem T, Polat S, Deveci M, Okursoy H, Gültaş HT (2010) Crop water stress index for assessing irrigation scheduling of drip irrigated broccoli (Brassica oleracea L. Var. Italica). Agric Water Manag 98(1):148–156. https://doi.org/10.1016/j.agwat.2010.08.013

Evans RG, Sadler EJ (2008) Methods and technologies to improve efficiency of water use. Water Resour Res 44(7). https://doi.org/10.1029/2007WR006200

Fao.org- crop water needs (Chap. 2)

FAO (2017) Water for sustainable food and agriculture a report produced for the G20 presidency of Germany. Rome

Franco JG, King SR, Volder A (2018) Component crop physiology and water use efficiency in response to intercropping. Eur J Agron 93:27–39. https://doi.org/10.1016/j.eja.2017.11.005

Fries A, Silva K, Pucha-Cofrep F, Oñate-Valdivieso F, Ochoa-Cueva P (2020) Water balance and soil moisture deficit of different vegetation units under semiarid conditions in the andes of southern Ecuador. Climate 8(2):30. https://doi.org/10.3390/cli8020030

Gashaw T (2015) The implications of watershed management for reversing land degradation in Ethiopia. Res J Agric Environ Manag 4(1):5–12

Gebregziabher G (2012) Watershed management in Ethiopia. Agwater Solution Solutions

Gee KD, Sojka S (2022) Maximizing the benefits of rainwater harvesting systems: review and analysis of selected case study examples. Resilient Water Management Strategies in Urban Settings. Springer, Cham, pp 77–117. https://doi.org/10.1007/978-3-030-95844-2_5

Gleeson T, Wada Y, Bierkens MFP, van Beek LPH (2012) Water balance of global aquifers revealed by groundwater footprint. Nature 488:197–200

Gong XY, Ma WT, Yu YZ, Fang K, Yang Y, Tcherkez G, Adams MA (2022) Overestimated gains in water-use efficiency by global forests. Glob Change Biol 28(16):4923–4934. https://doi.org/10.1111/gcb.16221

Gonzalez PR, Camacho PE, Montesinos P, García Morillo J, Rodríguez Díaz JA (2016) Influence of spatiotemporal scales in crop water foot printing and water use management: evidences from sugar beet production in Northern. Spain J Clean Prod 139:1485–1495

Haggblade S, Hazell PB, Reardon T (eds) (2007) Transforming the rural nonfarm economy: opportunities and threats in the developing world. Intl Food Policy Res Inst

Hatfield JL, Dold C (2019) Water-use efficiency: advances and challenges in a changing climate. Front Plant Sci 10:103. https://doi.org/10.3389/fpls.2019.00103

Hawkesford MJ, Araus JL, Park R, Calderini D, Miralles D, Shen T et al (2013) Prospects of doubling global wheat yields. Food Energy Secur 2(1):34–48. https://doi.org/10.1002/fes3.15

Hopken LM (2022) Towards reduced policy implementation barriers applicable to smart water resources management: a qualitative analysis. Dissertation, University of Twente

Hu Z, Piao S, Knapp AK, Wang X, Peng S, Yuan W et al (2022) Decoupling of greenness and gross primary productivity as aridity decreases. Remote Sens Environ 279:113120. https://doi.org/10.1016/j.rse.2022.113120

Ibok EE, Daniel EE (2014) Rural water supply and sustainable development in Nigeria: a case analysis of Akwa Ibom State. Am J Rural Dev 2(4):64–73

ICOLD (International Commission on Large Dams) (2020) World register of dams. Available at https://www.icold-cigb.org/GB/world_register/world_register_of_dams.asp

ILO (2020) Water for Improved Rural livelihoods. International Labour Office

International Energy Agency (IEA) (2012) Water for energy: is energy becoming a thirstier resource? Ch. 17.

International Water Management Institute (2010) Issue 10. https://en.wikipedia.org/wiki/Rainfed_agriculture

IWMI (International Water Management Institute) (2001) Climate and Water Atlas, IWMI, Colombo, Sri Lanka. CD-ROM

Jakeman AJ, Barreteau O, Hunt RJ, Rinaudo JD, Ross A, Arshad M, Hamilton S (2016) Integrated groundwater management: an overview of concepts and challenges. Integr Groundw Manage 3–20

Jiang Y, Wang XX, Meng H, Xu YW, Wang S, Wang SD (2022) Photosynthetic physiology performance and expression of transcription factors in soybean of water use efficiency difference. Russ J Plant Physiol 69(1):1–10. https://doi.org/10.1134/S102144372201006X

Kakpo A, Mills BF, Brunelin S (2022) Weather shocks and food price seasonality in Sub-Saharan Africa: evidence from Niger. Food Policy 112:102347. https://doi.org/10.1016/j.foodpol.2022.102347

Kalogirou SA (2001) Artificial neural networks in renewable energy systems applications: a review. Renew Sust Energ Rev 5(4):373–401

Karam F, Masaad R, Sfeir T, Mounzer O, Rouphael Y (2005) Evapotranspiration and seed yield of field grown soybean under deficit irrigation conditions. Agri Water Manag 75(3):226–244. https://doi.org/10.1016/j.agwat.2004.12.015

Katerji N, Mastrorilli M, Rana G (2008) Water use efficiency of crops cultivated in the Mediterranean region: review and analysis. Eur J Agron 28(4):493–507. https://doi.org/10.1016/j.eja.2007.12.003

Katerji N, Van Hoorn JW, Hamdy A, Mastrorilli M, Fares C, Ceccarelli S, Grando S, Oweis T (2006) Classification and salt tolerance analysis of barley varieties. Agri Water Manag 85(1–2):184–192. https://doi.org/10.1016/j.agwat.2006.04.006

Kaurin A, Mihelič R, Kastelec D, Grčman H, Bru D, Philippot L, Suhadolc M (2018) Resilience of bacteria, archaea, fungi and N-cycling microbial guilds under plough and conservation tillage, to agricultural drought. Soil Biol Biochem 120:233–245. https://doi.org/10.1016/j.soilbio.2018.02.007

Keating BA, Carberry PS, Bindraban PS, Asseng S, Meinke H, Dixon J (2010) Eco-efficient agriculture: concepts, challenges, and opportunities. Crop Sci 50:S–109. https://doi.org/10.2135/cropsci2009.10.0594

Kerr J (2002) Sharing the benefits of watershed management in Sukhomajri, India. Selling forest environmental services: Market-based mechanisms for conservation and development. pp 327–343

Kijne JW, Barker R, Molden D (eds) (2003) Water productivity in agriculture: limits and opportunities for improvements. Comprehensive Assessment of Water Management in Agriculture Series 1, CABI International, UK

Ku SB, Edwards GE, Tanner CB (1977) Effects of light, carbon dioxide, and temperature on photosynthesis, oxygen inhibition of photosynthesis, and transpiration in Solanum tuberosum. Plant Physiol 59(5):868–872. https://doi.org/10.1104/pp.59.5.868

Kumar A, Saini KS, Dasila H, Kumar R, Devi K, Bisht YS, Kaushik P (2023) Sustainable intensification of cropping systems under conservation agriculture practices: impact on yield, productivity and profitability of wheat. Sustainability 15(9):7468. https://doi.org/10.3390/su15097468

Lamptey S (2022) Agronomic practices in soil water management for sustainable crop production under rain fed agriculture of drylands in Sub-Sahara Africa. Afr J Agric Res 18(1):18–26. https://doi.org/10.5897/AJAR2021.15822

Lara MV, Andreo CS (2011) C4 plants adaptation to high levels of CO2 and to drought environments. Abiotic stress in plants-mechanisms and adaptations, pp 415–428

Lehner B, Liermann CR, Revenga C (2011) Highresolution mapping of the world's reservoirs and dams for sustainable river-flow management. Front Ecol Environ 9:494–502

Li Q, Li H, Zhang L, Zhang S, Chen Y (2018) Mulching improves yield and water-use efficiency of potato cropping in China: a meta-analysis. Field Crops Res 221:50–60. https://doi.org/10.1016/j.fcr.2018.02.017

Li Q, Chen Y, Sun S, Zhu M, Xue J, Gao Z et al (2022) Research on crop irrigation schedules under deficit irrigation-a meta-analysis. Water Resour Manag 36(12):4799–4817. https://doi.org/10.1007/s11269-022-03278-y

Liu J, Bu L, Zhu L, Luo S, Chen X, Li S (2014) Optimizing plant density and plastic film mulch to increase maize productivity and water-use efficiency in semiarid areas. Agron J 106:1138–1146. https://doi.org/10.2134/agronj13.0582

Massoud MA, Al-Abady A, Jurdi M, Nuwayhid I (2010) The challenges of sustainable access to safe drinking water in rural areas of developing countries: case of Zawtar El-Charkieh, Southern Lebanon. J Environ Health 72(10)

McCartney M, Rex W, Yu W, Uhlenbrook S, Von Gnechten R (2022) Change in global freshwater storage. IWMI Working Paper 202

Messager ML, Lehner B, Grill G, Nedeva I, Schmitt O (2016) Estimating the volume and age of water stored in global lakes using a geo-statistical approach. Nat Commun 7:13603

Messina S, Gonzalez F, Saldana C, Pena-Sandoval GR, Tadeo-Ceniceros HE, Juarez-Rosete CR, Nair PK (2022) Solar powered dryers in agricultural produce processing for sustainable rural development worldwide: a case study from Nayarit-Mexico. Clean Circular Bioeconomy 3:100027. https://doi.org/10.1016/j.clcb.2022.100027

Migdal JS (2015) Peasants, politics and revolution: pressures toward political and social change in the Third World. Princeton University Press

Milly PCD (1994) Climate, soil water storage, and the average annual water balance. Water Resour Res 30(7):2143–2156. https://doi.org/10.1029/94WR00586

Mishra PK (2017) Socio-economic impacts of climate change in Odisha: issues, challenges and policy options. J Clim Change 3(1):93–107

Molden DJ, Murray-Rust H, Sakthivadivel R, Makin (2003) I 2003 A water-productivity framework for understanding and action. In: Kijne, J.W., Barker, R., Molden, D., eds. Water productivity in agriculture: Limits and opportunities for improvements. Comprehensive Assessment of Water Management in Agriculture Series 1, CABI International, UK

Molden D, Oweis T, Steduto P, Bindraban P, Hanjra MA, Kijne J (2010) Improving agricultural water productivity: between optimism and caution. Agric Water Manag 97(4):528–535. https://doi.org/10.1016/j.agwat.2009.03.023

Mubeen M, Ahmad A, Wajid A, Khaliq T, Hammad HM, Sultana SR, Ahmad S, Nasim W, Fahad S (2016) Application of CSM-CERES-maize model in optimizing irrigated conditions. Outlook Agric 45(3):173–184. https://doi.org/10.1177/0030727016664464

Nijdam D, Rood T, Westhoek H (2012) The price of protein: review of land use and carbon footprints from life cycle assessments of animal food products and their substitutes. Food Policy 37(6):760–770. https://doi.org/10.1016/j.foodpol.2012.08.002

OECD (2022) - https://www.oecd.org

Oweis T, Hachum A (2009) 10 supplemental irrigation for improved rainfed agriculture in WANA Region. Rainfed Agriculture, 182

Oweis T, Hachum A, Pala M (2005) Faba bean productivity under rainfed and supplemental irrigation in northern Syria. Agric Water Manag 73(1):57–72. https://doi.org/10.1016/j.agwat.2004.09.022

Page KL, Dang YP, Dalal RC (2020) The ability of conservation agriculture to conserve soil organic carbon and the subsequent impact on soil physical, chemical, and biological properties and yield. Front Sustain Food Syst 4:31

Palanisami K, Ramesh T (2009) Water productivity at farm level in Bhavani Basin. Estimation, Challenges and Approaches, Tamil Nadu

Playan E, Mateos L (2006) Modernization and optimization of irrigation systems to increase water productivity. Agric Water Manag 80(1–3):100–116. https://doi.org/10.1016/j.agwat.2005.07.007

Pratibha G, Rao KV, Srinivas I, Sharma KL, Rao MS, Arunakumari H et al (2022) Conservation agriculture in rainfed areas. In Conservation Agriculture in India, Routledge, pp 71–93

Pretty J, Brett C, Gee D, Hine R, Mason C, Morison J et al (2001) Policy challenges and priorities for internalizing the externalities of modern agriculture. J Environ Plan Manag 44(2):263–283. https://doi.org/10.1080/09640560123782

Prihar SS, Gajri PR, Benbi DK, Arora VK (2000) Intensive cropping efficient use of water, nutrients, and tillage. Food Products, p 68

Qu X, Brame J, Li Q, Alvarez PJ (2013) Nanotechnology for a safe and sustainable water supply: enabling integrated water treatment and reuse. Acc Chem Res 46(3):834–843. https://doi.org/10.1021/ar300029v

Rahman MA, Islam AKMS (2008) Crop performance in bed formed by furrow maker. An unpublished research report. FMPHT Division, BRRI, Gazipur, Bangladesh

Rao CS, Gopinath KA, Prasad JVNS, Singh AK (2016) Climate resilient villages for sustainable food security in tropical India: concept, process, technologies, institutions, and impacts. Adv Agron 140:101–214. https://doi.org/10.1016/bs.agron.2016.06.003

Rashid MA (2005) Groundwater management for rice irrigation in Barind area of Bangladesh. Dissertation, Bangladesh Agricultural University, Mymensingh

Ray LI, Swetha K, Singh AK, Singh NJ (2023) Water productivity of major pulses-A review. Agric Water Manage 281:108249

Razzak A, Tanvir RMR, Rahman PG, Robiul IM, Yeasmin N (2022) Response of lentil varieties on yield and yield contributing character as influence by deficit irrigation. 4(2):68–83

Riaz F, Riaz M, Arif MS, Yasmeen T, Ashraf MA, Adil M et al (2020) Alternative and non-conventional soil and crop management strategies for increasing water use efficiency. Environment, climate, plant and vegetation growth. Springer, Cham, pp 323–338. https://doi.org/10.1007/978-3-030-49732-3_13

Rights C (2000) Substantive issues arising in the implementation of the International Covenant on Economic, Social and Cultural Rights

Rockstrom J, Barron J, Fox P (2002) Rainwater management for increased productivity among small-holder farmers in drought prone environments. Phys Chem Earth Parts A/B/C 27(11–22):949–959. https://doi.org/10.1016/S1474-7065(02)00098-0

Rosenzweig MR, Binswanger HP (1992) Wealth, weather risk, and the composition and profitability of agricultural investments. Econ J 103(416):56–78. https://doi.org/10.2307/2234337

Sarkar S, Sarkar A, Zaman A (2016) Yield, water use and economics of chickpea (*Cicer arietinum*) as influenced by different levels of irrigation and mulches. Ind J Agron 61(4):479–483

Serageldin I (1995) Water resources management: a new policy for a sustainable future. Water Int 20(1):15–21

Sharma BR, Scott CA (2005) Watershed management challenges: introduction and overview. Watershed Manage Challenges, 1

Singh R, Kundu DK, Bandyopadhyay KK (2010) Enhancing agricultural productivity through enhanced water use efficiency. J Agric Phys 10(2):1–15

Solomon KF, Labuschagne MF (2003) Variation in water use and transpiration efficiency among durum wheat genotypes grown under moisture stress and non-stress conditions. J Agric Sci 141:31–41. https://doi.org/10.1017/S0021859603003356

Song W, Loik ME, Cui H, Fan M, Sun W (2022) Effect of nitrogen addition on leaf photosynthesis and water use efficiency of the dominant species Leymus chinensis (trin.) Tzvelev in a semi-arid meadow steppe. Plant Growth Regul 98(1):91–102. https://doi.org/10.1007/s10725-022-00835-8

Sturdy JD, Jewitt GP, Lorentz SA (2008) Building an understanding of water use innovation adoption processes through farmer-driven experimentation. Phys Chem Earth Parts A/B/C 33(8–13):859–872. https://doi.org/10.1016/j.pce.2008.06.022

Tallis H, Polasky S (2009) Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. Ann N Y Acad Sci 1162(1):265–283. https://doi.org/10.1111/j.1749-6632.2009.04152.x

The United Nations World Water Development Report (2019) Leaving no one behind. UNESCO, Paris

Tian X, Engel BA, Qian H, Hua E, Sun S, Wang Y (2021) Will reaching the maximum achievable yield potential meet future global food demand? J Clean Prod 294:126285. https://doi.org/10.1016/j.jclepro.2021.126285

Venkatesh G, Gopinath KA, Reddy KS, Reddy BS, Prabhakar M, Srinivasarao C et al (2022) Characterization of biochar derived from crop residues for soil amendment, carbon sequestration and energy use. Sustainability 14(4):2295. https://doi.org/10.3390/su14042295

Verma AK, Yadav PN (2018) Productivity and water-use efficiency of linseed (Linum usitatissimum L.)-based cropping systems as influenced by integrated nutrient management under rainfed condition. J Soil Water Conserv 17(1):53–57. https://doi.org/10.5958/2455-7145.2018.00008.5

Wada Y, Flörke M, Hanasaki N, Eisner S, Fischer G, Tramberend S, Wiberg D (2016) Modeling global water use for the 21st century: the water futures and solutions (WFaS) initiative and its approaches. Geosci Model Dev 9(1):175–222

Wallace JS (2000) Increasing agricultural water use efficiency to meet future food production. Agric Ecosyst Environ 82(1–3):105–119. https://doi.org/10.1016/S0167-8809(00)00220-6

Wang GY, Han YY, Zhou XB, Chen YH, Ouyang Z (2014) Planting pattern and irrigation effects on water-use efficiency of winter wheat. Crop Sci 54:1166–1174. https://doi.org/10.2135/cropsci2013.06.0363

Wang G, Chen Z, Yang X, Cai G, Shen Y (2022) Effect of simulated precipitation regimes on sap flow and water use efficiency for xerophytic Caragana korshinskii. Ecol Indic 143:109309. https://doi.org/10.1016/j.ecolind.2022.109309

Wani SP, Maglinao AR, Ramakrishna A, Rego TJ (2003) Integrated watershed management for land and water conservation and sustainable agricultural production in Asia. Proceedings ADB-ICRISAT-IWMI Project Review and Planning Meeting, 10–14 December 2001, Hanoi, Vietnam. International Crops Research Institute for the Semi-Arid tropics, Patancheru, India

Wenyan W, Bing S, Zhilu L (1994) Drain-spacing calculation considering influence of evaporation. J Irrig Drain Eng 120:563–572

World bank (2022) https://www.worldbank.org/en/topic/climate-smart-agriculture

Wu B, Lin X, Ali MF, Wang D (2022) Development of an irrigation regime for winter wheat to save water resources by avoiding irrigation at anthesis stage. J Agron Crop Sci 209(1):188–203. https://doi.org/10.1111/jac.12615

WWAP-United Nations World Water Assessment Programme (2014) The United Nations World Water Development Report 2014 (Water and Energy. Paris, UNESCO,2014)

WWAP-World Water Assessment Programme (Nations Unies) (2018) The United Nations World Water Development Report 2018. United Nations Educational Sci Cult Organ New York, United States. www.unwater.org/publications/world-water-development-report-2018/

Yadav M, Vashisht BB, Jalota SK, Kumar A, Kumar D (2022) Sustainable water management practices for intensified agriculture. soil-water, agriculture, and climate change: exploring linkages. Springer International Publishing, Cham, pp 131–161. https://doi.org/10.1007/978-3-031-12059-6_8

Young OR (1999) Institutional Dimensions of Global Environment Change. International Human Dimensions Program Report 9, Bonn, Germany

Zahoor SA, Ahmad S, Ahmad A, Wajid A, Khaliq T, Mubeen M et al (2019) Improving water use efficiency in agronomic crop production. Agronomic Crops 2:13–29. https://doi.org/10.1007/978-981-32-9783-8_2

Zhang H, T Oweis (1999) Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agric Water Manag 38(3):195–211. https://doi.org/10.1016/S0378-3774(98)00069-9

Zhang Q, Wang Z, Miao F, Wang G (2017) Dryland maize yield and water-use efficiency responses to mulching and tillage practices. Agron J 109:1196–1209. https://doi.org/10.2134/agronj2016.10.0593

Zhang Y, Deng J, Qin B, Zhu G, Zhang Y, Jeppesen E, Tong Y (2022) Importance and vulnerability of lakes and reservoirs supporting drinking water in China. Fundam Res 3(2):265–273. https://doi.org/10.1016/j.fmre.2022.01.035

Zhou H, Kang S, Li F, Du T, Shukla MK, Li X (2020) Nitrogen application modified the effect of deficit irrigation on tomato transpiration, and water use efficiency in different growth stages. Sci Hortic 263:109112. https://doi.org/10.1016/j.scienta.2019.109112

Authors and Affiliations

Manish Yadav[1] · B. B. Vashisht[1] · S. K. Jalota[1] · T. Jyolsna[1] · Samar Pal Singh[2] · Arun Kumar[3] · Amit Kumar[4] · Gurjeet Singh[5,6]

✉ Manish Yadav
manish.soil017@gmail.com

[1] Department of Soil Science, Punjab Agricultural University, Ludhiana, Punjab 141004, India

[2] Krishi Vigyan Kendra, Ujwa, New Delhi 110073, India

[3] Livestock Research Station, Rajasthan University of Veterinary and Animal Sciences, Bikaner, Rajasthan 334001, India

[4] Division of Agronomy, ICAR research complex for NEH Region, Gangtok, Sikkim 737102, India

[5] Department of Plant Breeding and Genetics, Punjab Agricultural University, Ludhiana, Punjab 141004, India

[6] Department of Soil and Crop Sciences, Texas A&M University, AgriLife Research Center, Beaumont, TX 77713, USA