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FULL-LENGTH RESEARCH ARTICLE

Water Use in Rice Crop Cultivation in India: A Quantitative Assessment

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Abstract

Water management is critical for sustainable paddy cultivation in India where rice plays a major role in food security. This study explores the water footprint (L kg^{-1}) and water productivity (kg m^{-3}) of paddy cultivation across various regions in India, taking into account both green (rainfed) and blue (irrigated) water components. The water footprints and water productivity were calculated using spatial and temporal data on rainfall, soil, irrigation sources and crop coefficients data across diverse agro-ecological zones in India. Regional averages were derived from meteorological and hydrological datasets, including both green and blue water inputs. On an average, it takes 1500–2000 L of water to produce 1 kg of paddy in India, with significant regional variations influenced by soil, climate, irrigation practices, crop productivity. These figures are lower than those of Bangladesh (2179–3268 L kg^{-1}), Indonesia (1886–3030 L kg^{-1}) and Philippines (900–3333 L kg^{-1}), but higher than those of China ($\sim$ 1321 L kg^{-1}) and Vietnam ($\sim$ 952 L kg^{-1}). Regions like Northeastern states depend on rainfed paddy cultivation due to abundant rainfall, with green water footprints ranging from 1155 to 2660 L kg^{-1}. There is significant potential for developing water harvesting infrastructure in this region. In contrast, regions like Punjab and Haryana, which practice intensive irrigation and ground water extraction, show higher water footprints ranging from 2270 to 2672 L kg^{-1}, highlighting the need for improved water management strategies. The water footprint of paddy is higher compared to that of wheat and maize but can be similar to cotton, mustard and even groundnut with efficient irrigation management. The study emphasizes the importance of tailored approaches to enhance water productivity, reduce water footprints, and ensure sustainable rice production in the context of climate change to achieve the Sustainable Agricultural Goals.

Keywords Water footprint · Water productivity · Paddy · Irrigation management · Sustainable agriculture · Rice

Introduction

Water is a critical resource for crop production, especially in the context of climate change. In India, paddy is a major staple crop and a significant consumer of water resources.

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The country cultivates rice crop (paddy) on 47.8 M ha of land, producing 135.7 Mt with an average yield of 2838 kg ha^{-1}, accounting for 40% of total food grain production and sustaining over 65% of the population [24, 49]. Paddy is often considered as a water-intensive crop, with a water footprint ranging from 2500 to 3500 L kg^{-1} [39, 44]. This footprint includes both green (rainfall) and blue (irrigation) water, with rainfed systems primarily dependent on green water. The water requirement for paddy varies regionally, influenced by climatic factors such as potential evapotranspiration (PET) and water sources (rainfed vs. irrigated) [17–19, 40]. Enhancing water use efficiency and minimizing water loss in paddy cultivation is crucial. One strategy is to reduce the water footprint per kg of paddy produced [14]. Water footprint is measured as grain yield per unit of irrigation water (irrigation water footprint), total water input (total water footprint), or water lost through evapotranspiration (crop water footprint) [56, 58]. Sustainable rice crop production is crucial for achieving the Sustainable Development Goals (SDGs), particularly for a populous country like India. Enhancing productivity, profitability, input use efficiency, and climate resilience in paddy cultivation is essential to meet these goals [33, 60].

In India, 52% of rice crop cultivation is under mostly irrigated condition, using approximately 40% of all irrigation water resources. Improving water use efficiency is crucial in paddy cultivation, given that a substantial amount of applied water, typically 60–83%, is lost to deep percolation [46, 49]. Rice crop require 400–700 mm of total water for its ET needs, varying from 600–700 mm in the dry- to 400–500 mm in the wet season. However, in conventional transplanting, an additional amount of 150–250 mm water is used for puddling operation, and 100–500 mm water is wasted due to seepage and percolation losses in heavy clay, and 1500–3000 mm in loamy and sandy soils [9].

Reducing the water footprint and increasing the water productivity of paddy cultivation through irrigation water management, agronomic practices, and advanced tools and techniques is a critical research priority. This article aims to investigate the regional green (effective rainfall, ER) and green + blue (ER + irrigation water) water requirements and water productivity for paddy production in India, providing insights into the actual water needs across climates and geographical locations. Additionally, it emphasizes the importance of developing water harvesting infrastructure in rainfall-surplus regions of India (e.g., Northeastern region) to optimize water accounting, reduce water footprint, and increase water productivity in paddy cultivation.

Materials and Methods

Calculating Water Requirement of Paddy in India

The Food and Agriculture Organization (FAO) defines crop water requirement as 'the amount of water needed to compensate for the water loss through evapotranspiration of a crop [7]. This definition assumes ideal conditions, where the crop is disease-free, grown in large fields with non-restrictive soil conditions, including optimal soil water and fertility levels, and achieving full production potential based on the given growing environment. The crop water requirement is determined by two major parameters: climate (Reference ET or ET0) and crop characteristics (Kc and growth stages):

$$\text{Total crop water requirement (mm)} = (ET_0 * Kc * \text{growing period}) \quad (1)$$

The ET_0 is the amount of ET that occurs on a grass surface (mm/day). Monthly mean Penman–Monteith ET_0 (FAO-56 PM ET0) values for paddy-growing areas in India were collected from IMD publications [23, 45]. The crop coefficient (Kc) in paddy varies throughout the growing period due to changes in groundcover, crop height, and leaf area. In India, Kc values were selected for three growth stages in rice: initial, mid-season, and end season [7]. The length of growing season is 30–35 days for each stage, except for the mid-season, which lasts 60–80 days, resulting in a total growing period of 120–150 days. The crop coefficient values were taken as 1.1, 1.2, and 0.80 for Kc-initial, Kc-mid, and Kc-end, respectively. The product of ET0 and Kc is also known as crop ET (ETc).

Calculating Water Footprint

The water footprint (WF) includes both direct and indirect water use by a consumer or product [25, 29]. It comprises of three components: blue, green, and grey WF [12, 28]. The green WF represents the total rainfall or soil moisture available to plants in the unsaturated zone. The blue WF denotes the volume of fresh surface or groundwater used in the production of goods and services. Assessing the WF is essential for raising awareness about the global water crisis [14]. The consumptive water footprint for paddy production reflects the freshwater used throughout the cultivation process. In rainfed paddy cultivation, green water is the primary component, whereas for irrigated paddy production, blue water is the major component.

The water footprint (WF) for paddy in different Indian states was calculated using CROPWAT 8.0 (https://www.fao.org/land-water/databases-and-software/cropwat/en/), following the methodology outlined by Nayak et al. [47].

Table 1 Water requirement (mm) of paddy across different regions of India

Region/state	Duration of rice crop[1]						Total water requirement (mm)[2]		
	Kharif		Rabi		Summer		Kharif	Rabi	Summer
	Sowing	Harvesting	Sowing	Harvesting	Sowing	Harvesting			
North									
Haryana	May–Aug	Sep–Nov					467–830	–	–
Punjab	May–Aug	Sep–Nov	–	–	–	–	467–833	–	–
West Uttar Pradesh	May–Aug	Sep–Nov					467–734	–	–
Himachal Pradesh	June–July	Sep–Nov	–	–	–	–	540–675	–	–
Jammu & Kashmir	–	–	Apr–July	Sep–Dec	–	–		637–871	–
West								–	
Gujarat	–	–	Jun–Aug	Oct–Dec	–	–	–	534–635	–
Maharashtra	–	–	Jun–July	Oct–Dec	–	–	–	635–637	–
Rajasthan	–	–	July–Aug	Oct–Dec	–	–	–	494–534	–
North-East									
Assam	Mid Feb–Apr	June–July	June–Aug	Nov–Dec	Dec–Feb	May–June	682–750	534–712	750–768
East									
Bihar	May–July	Sep–Oct	July–Sep	Nov–Dec	Jan–Feb	May–June	494–718	534–617	681–750
East Madhya Pradesh	June–Aug	Mid Sep–Mid Dec	–	–	–	–	534–540	–	–
Orissa	May–June	Sep–Oct	June–Aug	Dec–Jan	Dec–Jan	May–June	635–718	534–635	768–864
East Uttar Pradesh	May–July	Sep–Nov	July–Aug	Nov–Dec	Jan–Feb	Apr–June	637–789	609–617	507–829
West Bengal	Mar–June (B)	July–Nov	Apr–June (B)	Nov–Dec	Oct–Feb	Apr–May	692–865	789–994	619–627
	May–June (T)	July–Nov	July–Aug (T)	Nov–Dec			418–529	609–617	–
South									
Andhra Pradesh	Mar–April	July–Aug	May–June	Nov–Dec	Dec–Jan	April–May	682–750	866–937	681–750
Karnataka	May–Aug	Sep–Dec	June–Oct	Nov–March	Dec–Feb	April–July	572–766	592–759	681–930
Kerala	April–June	Aug–Oct	Sep–Oct	Jan–Feb	Dec–Jan	March–Apr	635–828	510–581	681–750
Tamil Nadu			*Early Samba*		*Late Samba*				
Sonavari	April–May	July–Aug	June–July	Nov–Dec	Oct–Nov	March–Apr	624–682	684–759	627–665
			Samba	*Navarai*					
Kar	May–June	Aug–Sep	July–Aug	Dec–Jan	Dec–Jan	April–May	540–624	604–684	681–750
			Thaladi/Pishanam						
Kuruvai	June–July	Sep–Oct	Sep–Oct	Dec–Jan	–	–	540–570	396–430	–

[1]Status Paper on Rice: Directorate of Rice Development, Government of India, Ministry of Agriculture & Farmer's Welfare, Patna, Bihar (https://drdpat.bih.nic.in/Downloads/Status-Paper-on-Rice.pdf)

[2]Total water requirements (mm) = (ETo * growing period * Kc)

Variations in the WF for paddy are influenced by climatic factors such as temperature, rainfall, and potential evapotranspiration (PET), as well as soil types and irrigation practices. States with higher rainfall mainly rely on green water, while those with lower rainfall use supplement irrigation, leading to increase in blue water usage (Table 1). The average yield of kharif paddy over the past five years was considered for this analysis. The state-wise

Table 2 Water requirement (litres, L) of paddy to produce 1 kg grain yield in comparison with other major crops in India

Crop	Water requirement (mm)	Water footprint (L kg^{-1})	References	Comments
Rice Crop (Paddy)	300–500	850–2500	[8, 15, 58]	Includes nursery and main field preparation
Wheat	70–120	500–1250	[58]	
Maize	70–160	400–900	[31]	Kharif maize
Sugarcane	15–25	3000–5000	[6]	20% higher in tropics
Cotton	150–350	1000–2500	[21]	Most water requirement at mid-season
Mustard	200–250	1500–2000	[25, 26]	Max: 2 irrigations (must at pod forming stage); No frequent irrigation
Chickpea	30–150	1700	[22]	Drought tolerant; required supplemental irrigation only
Pigeon pea	200–250	3000–5000	[55]	
Groundnut	200–300	2500	[20, 21, 30]	Early to late developmental stage-similar water requirement; Supplemental irrigation required at flowering stage
Soybean	120–250	500–1200	[16, 51]	Highest requirement between flowering to pod fill—most sensitive stage; irrigated yield 1.5 times higher than rainfed yield

irrigated and rainfed yields were estimated based on available data from 4 to 5 districts of each state [3–5, 37, 41, 61]. The WF was partitioned into green and blue components. In regions like Northeastern states (e.g., Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland) where effective rainfall meets crop water requirements (i.e., ET), only the green water component (ER) was selected. Conversely, regions like Punjab, Haryana, and Rajasthan use both irrigation and ER to meet ET, hence both green (ER) and blue water components (net and gross irrigation water requirement) were included in the WF calculation. A 40% irrigation efficiency was considered for water footprint calculation based on gross irrigation water requirement [34].

Water Productivity Mapping of Paddy

In our analysis, we calculated Physical Water Productivity (PWP) of rice crop on a state-by-state basis for both irrigated and rainfed condition. PWP is defined as the ratio of paddy yield to consumptive water use [54]. We factored in a head rice recovery percentage of 0.66 to convert rice yield to paddy yield. The average paddy yields over five years, from 2018–2019 to 2022–2023 was used for both irrigated and rainfed conditions across Indian states.

Results and Discussion

Water Requirements for Rice Cultivation in India

Table 1 shows the water requirements for rice crop (paddy) cultivation in various regions of India across three seasons. The water requirements for the north, north-east, west, and south regions of India range from 418–865 mm, 396–937 mm, and 507–930 mm for *kharif*, *rabi*, and summer seasons, respectively. The overall average values for India are 634 mm, 643 mm, and 718 mm for kharif, rabi, and summer, respectively.

For one ha of rice cultivation, the water requirement ranges from 6340 to 7180 m^3 (1 ha = 10,000 m^2). With the average rice yield in India being 3000 kg/ha, total water requirement is 2.1–2.4 m^3 or 2100–2400 L per kg of rice. This gives a water productivity range of 0.42–0.47 kg/m^3. It is important to note that the calculated water requirement exceeds the long-term average rainfall during the southwest monsoon in India (which is 880.6 mm, according to IMD for the period 1961–2010).

The water footprint associated with the cultivation of paddy in India is found to be lower when compared to that of Bangladesh (2179–3268 L kg^{-1}) [1], Indonesia (1886–3030 L kg^{-1}) [2], and the Philippines (900–3333 L kg^{-1}) [58]. However, it is higher in comparison to China's ($\sim$ 1321 L kg^{-1}) [27] and Vietnam's ($\sim$ 952 L kg^{-1}) [58] water footprints. Table 2 illustrates water requirements for different major crops including rice cultivation in India as per estimation based on various researchers. The water footprint of paddy exceeds that of wheat (500–1250 L kg^{-1}) and maize (400–900 L kg^{-1}). However, with efficient irrigation management, it can closely resemble that of cotton (1000–2500 L kg^{-1}), mustard (1500–2000 L kg^{-1}), and even groundnuts (2500 L kg^{-1}).

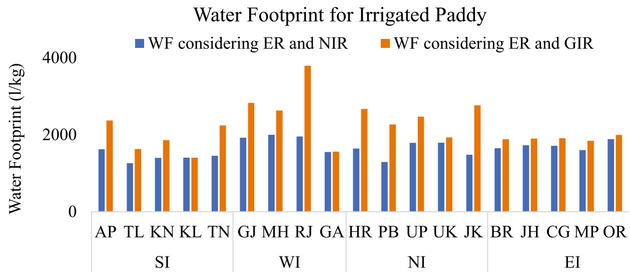

Fig. 1 State wise water footprint for irrigated Paddy. Note: ER: effective rainfall, NIR: net irrigation water requirement to fulfil crop ET demand. GIR: gross irrigation requirement computed considering efficiency of irrigation system as 40%. ER is green water whereas, NIR and GIR are blue water. AP: Andhra Pradesh, TL-Telangana, KN: Karnataka, KL: Kerala, TN: Tamil Nadu, GJ: Gujrat, MH: Maharashtra, RJ: Rajasthan, GA: Goa, HR: Haryana, PB: Punjab, UP: Uttar Pradesh, UK: Uttarakhand, BR: Bihar, JK: Jharkhand, CG: Chhattisgarh, MP: Madhya Pradesh, OR: Odisha, WB: West Bengal, SI: Southern India Region, WI: Western India region, Northern India Region (NI), EI: Eastern India region

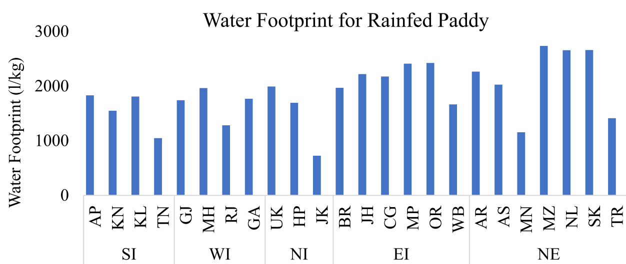

Fig. 2 State wise water footprint for Rainfed Paddy. Note: AP: Andhra Pradesh, KN: Karnataka, KL: Kerala, TN: Tamil Nadu, GJ: Gujrat, MH: Maharashtra, RJ: Rajasthan, GA: Goa, UK: Uttarakhand, HP: Himachal Pradesh, JK: Jammu and Kashmir, BR: Bihar, JK: Jharkhand, CG: Chhattisgarh, MP: Madhya Pradesh, OR: Odisha, WB: West Bengal, AR: Arunachal Pradesh, AS: Assam, MN: Manipur, MZ: Mizoram, NL: Nagaland, SK: Sikkim, TR: Tripura. SI: Southern India Region, WI: Western India region, Northern India Region (NI), EI: Eastern India region, NE: Northeastern Region

Regional Variation of Water Footprint in India

North Indian Region (NI)

Northern states such as Punjab, Haryana, Uttarakhand, Western Uttar Pradesh, Himachal Pradesh, and Jammu & Kashmir showed variation in green and blue water footprints. For example, Punjab, Haryana and Uttar Pradesh, which primarily practice irrigated agriculture, utilize both the green (ER) and blue (irrigation) water to meet their ET requirement. The water footprint, which consists of green and blue water components in these states, varies from 1292–1795 L kg^{-1} considering ER + NIR (net irrigation requirement). However, the water footprint for the combined use of ER + GIR (gross irrigation requirement) with an irrigation efficiency of 40% varies from 1932 to 2765 L kg^{-1} (Table 3, Fig. 1). This highlights the potential to reduce the water footprint by adopting improved irrigation methods, thus minimizing losses due to percolation or deep drainage. This observation is significant for considering the suitability of rice cultivation and implementing improved irrigation management policies in these regions.

East Indian Region (EI)

This region includes Bihar, Chhattisgarh, Jharkhand, Madhya Pradesh, Odisha and West Bengal. In India, the Ganges and Mahanadi River basins are the major rice-growing regions with the highest intensity of rice cultivation. This region uses both green (ER) and blue (irrigation) water for rice cultivation. The green water footprint is higher compared to green + blue water footprint in this region. The green water footprint for rainfed rice cultivation varies from 1664 to 2422 L kg^{-1} (Fig. 2). The water footprint, comprising green and blue water component in these states, varies from 1517–1886 L kg^{-1} considering ER + NIR. Meanwhile, the water footprint for the combined use of ER + GIR with an irrigation efficiency of 40% varies from 1558 to 1995 L kg^{-1} (Table 3, Fig. 1).

North Eastern Region (NE)

This region receives abundant rainfall, so paddy is predominantly grown under rainfed conditions. Therefore, the green water footprints for the states (e.g., Arunachal Pradesh, Assam, Manipur, Tripura, Sikkim) were only estimated. The green water footprint for rainfed rice cultivation in this region ranges from 1155 to 2660 L kg^{-1}. The higher values of green water footprint for Nagaland, Mizoram and Sikkim are due to lower paddy yield in these states (Table 3, Fig. 2). The crop water requirement (i.e., ET) is supplied by rainfall and there is significant surplus of green water that is lost. This highlights the potential for establishing water harvesting infrastructure in these regions. Rice cultivation is more sustainable in these areas as the water requirement for paddy is solely met by rainfall, and there is minimal to zero use of blue/irrigation water in this region.

West Indian Region (WI)

This region (Gujarat, Maharashtra, and Rajasthan) mainly grows paddy under rainfed conditions. However, the effective rainfall is barely enough to meet the crop water requirement (i.e., ET), so supplemental irrigation is also used. The green water footprint for this region varies from 1282–1963 L kg^{-1}. When considering ER + NIR, the total water footprint (green and blue water) for these states vary from 1552–1998 L kg^{-1}. Additionally, when combining ER + GIR with an irrigation efficiency of 40% the water

Table 3 State wise irrigated and rainfed *kharif paddy* yield and water footprint in India

Regions	States	Average Kharif yield from 2018–2023 (t/ha)	Irrigated Paddy yield (tha^{-1})) from 2018–2023	Rainfed Yield (t ha^{-1}) from 2018–2023	Water Footprint (L kg^{-1})		
					For irrigated rice (Green + Blue water)		For Rainfed Paddy (Green water, i.e. ER)
					Based on Effective Rainfall + Net Irrigation	Based on Effective Rainfall + Gross Irrigation	
SI	Andhra Pradesh	4.8	4.8	3.0	1625.0	2371.7	1831.1
	Telangana	5.1	5.1	–	1261.6	1630.1	–
	Karnataka	4.7	4.9	3.5	1401.8	1859.2	1549.7
	Kerala	4.2	4.4	3.4	1406.6	1406.6	1808.5
	Tamil Nadu	5.3	5.4	4.7	1453.7	2242.8	1047.2
WI	Gujarat	3.5	3.7	2.8	1926.0	2828.6	1741.1
	Maharashtra	3.2	3.7	3.0	1998.7	2629.8	1963.6
	Rajasthan	3.7	4.1	2.3	1954.7	3793.6	1282.4
	Goa	4.1	4.5	3.9	1552.0	1563.4	1768.1
NI	Haryana	5.1	5.1	–	1640.5	2672.7	–
	Punjab	6.4	6.4	–	1292.3	2270.3	–
	Uttar Pradesh	4.1	4.1	–	1787.7	2468.5	–
	Uttarakhand	3.9	4.0	3.4	1795.0	1932.4	1992.3
	Himachal Pradesh	3.1	–	2.4	–	–	1695.4
	Jammu and Kashmir	3.2	3.3	2.8	1479.1	2764.8	725.4
EI	Bihar	4.1	3.9	3.0	1649.1	1885.2	1968.9
	Jharkhand	3.0	4.0	2.9	1728.5	1903.6	2220.0
	Chhattisgarh	3.1	3.7	2.7	1715.3	1910.3	2175.9
	Madhya Pradesh	3.2	3.8	2.3	1600.6	1842.4	2411.1
	Odisha	3.1	3.7	2.8	1886.6	1995.5	2422.9
	West Bengal	4.2	4.5	4.0	1517.5	1558.5	1664.4
NE	Arunachal Pradesh	2.8	–	2.8	–	–	2266.0
	Assam	3.1	–	3.1	–	–	2027.0
	Manipur	4.5	–	4.5	–	–	1155.4
	Mizoram	2.4	–	2.4	–	–	2735.1
	Nagaland	2.4	–	2.4	–	–	2657.4
	Sikkim	2.6	–	2.6	–	–	2659.9
	Tripura	4.6	–	4.6	–	–	1413.3

[#]In above table green water refers to effective rainfall (ER); blue water refers to net irrigation requirement (NIR) and Gross irrigation requirement (GIR). Gross irrigation requirement (GIR) = NIR/Irrigation efficiency, where irrigation efficiency for surface irrigation was considered as 0.4. All calculations were made state-wise. Paddy Productivity = Milled rice productivity (t/ha) / Head rice recovery during milling (considered as 0.66)

footprint ranges from 1563–3793 L kg^{-1} (Table 3, Fig. 1). There is significant potential to reduce the water footprint in this region through the adoption of efficient irrigation methods and improved varieties.

Table 4 Summary of regional water footprint for paddy cultivation in India: productivity challenges and suggested policy interventions

Region	Rice cultivation mostly under	Water footprint based on value (L kg^{-1})	Productivity challenges	Proposed solutions/policy interventions	
North Indian Region (NI)	Irrigated condition	ER + NIR	1292–1795	High water footprint due to inefficient irrigation practices, mostly over extraction of ground water	Reduce rice cultivation under flooded conditions; adopt the DSR method to minimize water loss and groundwater over-extraction; cultivate short-duration, high-yielding paddy varieties; and diversify with less water-intensive crops, especially in the Central Punjab region
		ER + GIR	1932–2765		
East Indian Region (EI)	Rainfed and Irrigated Condition	ER	1664–2422	Less irrigation efficiency; issue of erratic rainfall in rain fed ecologies; less technological adoptions by farmers	Practice DSR, AWD (in irrigated areas) method for paddy cultivation; cultivate moisture stress tolerant climate resilient varieties; provide supplemental irrigation in rainfed areas; practice crop diversification in bunded upland ecology
		ER + NIR	1517–1886		
		ER + GIR	1558–1995		
North Eastern Region (NE)	Rainfed Condition	ER	1155–2660	Low yield of paddy; Low adoption and availability of improved irrigation practices and farm mechanization	Establish water harvesting infrastructure in hills; adopt high yielding rice varieties; use small farm implements and machineries for enhancing input use efficiency and water footprint of paddy
West Indian Region (WI)	Rainfed and Irrigated Condition	ER	1282–1963	Insufficient effective rainfall to meet ET; erratic rainfall; reliance on supplemental irrigation; less irrigation efficiency	Implement efficient irrigation methods in command areas; adopt high yielding paddy varieties; Replace paddy with more suitable crops in non-command areas where rainfall is insufficient for its production
		ER + NIR	1552–1998		
		ER + GIR	1563–3793		
Southern Region (SI)	Rainfed and Irrigated Condition	Rainfed	1047–1831	Varying irrigation conditions and less irrigation efficiency technology adoption in agricultural sector is very low due to various socio-economic and bio-physical constraints	Practice DSR and AWD; adopt high yielding paddy varieties
		ER + NIR	1261–1625		
		ER + GIR	1406–2372		

[#]In above table green water refers to effective rainfall (ER); blue water refers to net irrigation requirement (NIR) and Gross irrigation requirement (GIR)

Southern Region (SI)

The southern region of India, including Andhra Pradesh, Telangana, Karnataka, Kerala, and Tamil Nadu, is known for its major rice-growing areas These include deltaic tracts of Krishna, Godavari, and Cauvery rivers, as well as the non-deltaic rainfed areas of Andhra Pradesh and Tamil Nadu. Rice cultivation in this region occurs under rainfed (except Telangana) and irrigated conditions.

The green water footprint for rice crop in this region ranges from 1047–1831 L kg^{-1}. The total water footprint. Which includes both green and blue water components vary from 1261–1625 L kg^{-1} based on ER + NIR. When considering ER + GIR with an irrigation efficiency of

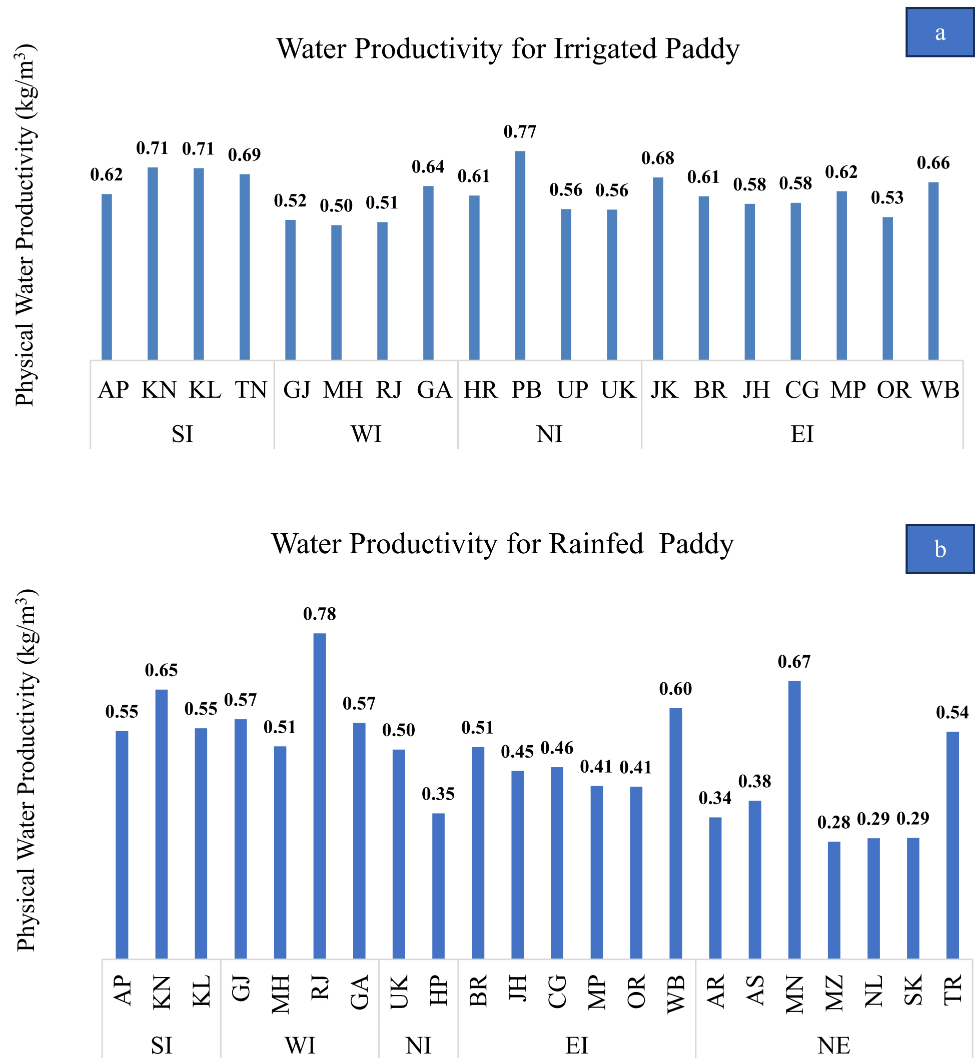

Fig. 3 Physical Water productivity (kg/m^3) of *kharif* irrigated paddy production (a) and Physical Water productivity of *kharif* rainfed paddy production. Note: AP: Andhra Pradesh, TL: Telangana, KN: Karnataka, KL: Kerala, TN: Tamil Nadu, GJ: Gujrat, MH: Maharashtra, RJ: Rajasthan, GA: Goa, HR: Haryana, PB: Punjab, UP: Uttar Pradesh, UK: Uttarakhand, BR: Bihar, JK: Jharkhand, CG: Chhattisgarh, MP: Madhya Pradesh, OR: Odisha, WB: West Bengal, SI: Southern India Region, WI: Western India region, Northern India Region (NI), EI: Eastern India region, AR: Arunachal Pradesh, AS: Assam, MN: Manipur, MZ: Mizoram, NL: Nagaland, SK: Sikkim, TR: Tripura. SI: Southern India Region, WI: Western India region, Northern India Region (NI), EI: Eastern India region, NE: Northeastern Region

40%. The water footprint ranges from 1406–2372 L kg^{-1} (Table 3, Fig. 1).

Table 4 presents an overall summary of the regional water footprint for paddy cultivation in India, along with productivity challenges and suggested technological and policy interventions.

Water Productivity Mapping of Paddy

Based on the average paddy productivity data from the last five years, water productivity values varied across different states in India. Punjab has the highest land productivity for paddy at 6.4 t ha^{-1} (Table 3). Under irrigated conditions, Punjab and Haryana have high PWP values of 0.77 and 0.61 kg m^{-3}, respectively (Fig. 3a). The PWP of paddy in India ranges from 0.30–0.80 kg m^{-3} with an average value of is 0.50 kg m^{-3}. Most states have a PWP below the average value. The Northeastern region of India, which mainly practices rainfed rice cultivation, has lower PWP values ranging from 0.29 to 0.67 kg m^{-3} with an average value of 0.40 kg m^{-3} mainly due to the less paddy productivity (Fig. 3b). Moreover, the PWP in Eastern Indian Region ranges from 0.34–0.6 kg m^{-3} indicating significant potential for improving paddy productivity through appropriate policies and practices. The state-wise PWP variability under irrigated and rainfed condition is shown in Fig. 4a, b.

In 2018, a NABARD-ICRIER joint study released the 'Water Productivity Mapping of Major Indian Crops' for 10 major crops in India, which included rice [54]. The study measured water productivity at three levels: Physical Water Productivity (PWP, output per unit of consumptive water use), Irrigation Water Productivity (IWP, output per unit of irrigation water applied) and Economic Water Productivity (EWP, economic output produced per unit of water consumed or irrigation water applied). The study reported a higher value of PWP for Punjab (0.57 kg/m^3) and Haryana (0.40 kg/m^3), respectively. However, the IWP

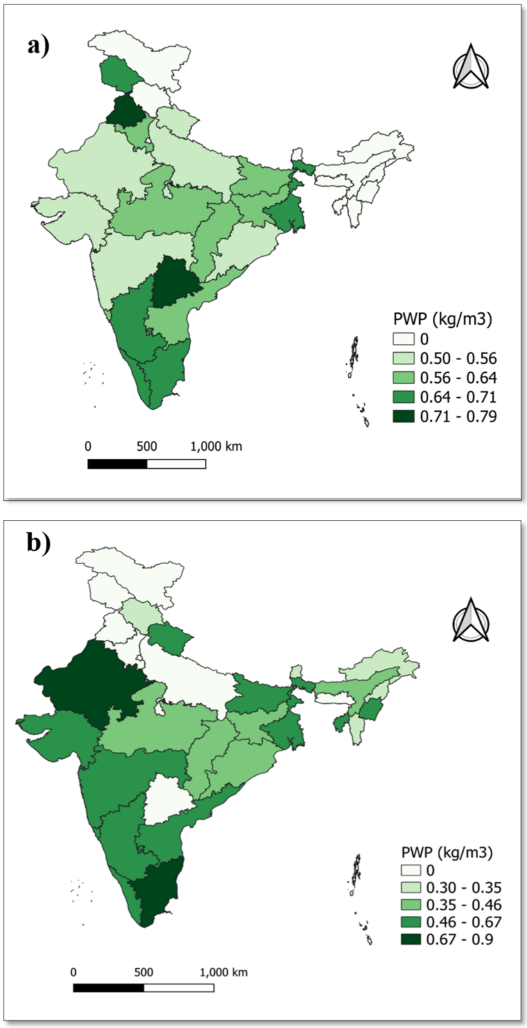

Fig. 4 Spatial variability maps of Physical Water productivity of irrigated kharif paddy production (**a**) and rainfed kharif paddy production (**b**)

in these states is relatively low, at 0.22 kg/m^3, indicating inefficient irrigation water use. The almost free electricity policy in agriculture in Punjab and Haryana, and assured Minimum Support Price (MSP) has led to indiscriminate groundwater exploitation.

High land productivity due to assured irrigation, combined with an effective and assured procurement policy for paddy, further encourages farmers to cultivate this crop despite the rising water sustainability issues. In contrast, states like Chhattisgarh and Jharkhand displayed high irrigation water productivity but have low irrigation coverage (32% and 3% respectively), resulting in lower land productivity. The underdeveloped procurement policy for paddy and low power supplies to agriculture in these states has further resulted in lower profitability levels of rice cultivation, despite the hydrological suitability of the region. Therefore, there exists a serious misalignment in rice cropping patterns with respect to the water resource availability in India. Effective demand-side, as well as supply-side policies, are needed to address this issue.

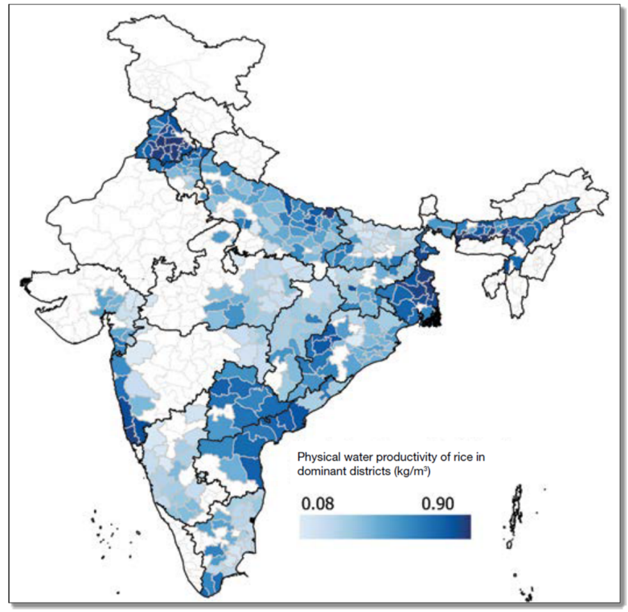

Fig. 5 Physical water productivity of paddy in different districts of India [Physical water productivity = Grain yield/(Total consumptive crop water use), kg/m^3]

NABARD's data shows the variation of PWP for paddy in different districts of India estimated in Fig. 5. A majority of the districts have a lower PWP value compared to the average PWP for India, yet these districts contribute 44% of the total production. These districts are mainly located in eastern Uttar Pradesh, Bihar, Madhya Pradesh, Tamil Nadu, Karnataka, Jharkhand, and Odisha. Therefore, it is suggested that the national rice development efforts should focus primarily on these districts. On the other hand, the remaining districts have a higher PWP than the average. These districts cover 45% of the area and contribute 56% to total production. They are primarily situated in Assam, Punjab, western Uttar Pradesh, West Bengal, Andhra Pradesh, and Odisha, among others. It is important to note that there are vast variations within the states. Therefore, policies and practices need to be carefully implemented and executed at the district level. The map indicates considerable scope of improvement in rice productivity. Higher water productivity is generally seen in the districts that have greater control and reliability of the water supply or through use of groundwater through affordable energy sources [54].

The Case of Punjab and Haryana

The groundwater levels in Punjab dropped from 12.10 m in 2009–2010 to 18.06 m in 2018–2019, while in Haryana,

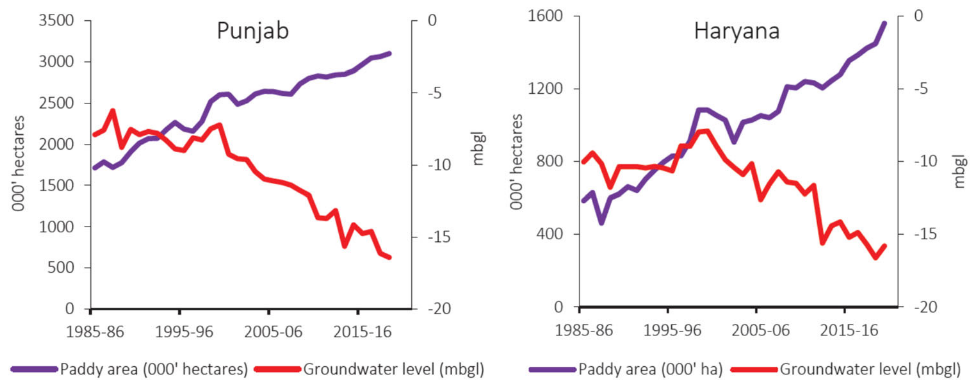

Fig. 6 Paddy acreage and groundwater level in Punjab and Haryana over three decades

Table 5 Water saving technologies for rice paddy cultivation

Practice	Effect on Water Footprint/Water Productivity/Water Use of rice paddy	References
System of Rice Intensification (SRI)	Decreases the crop water footprint by using 25–73% less water; thereby reducing percolation loss and increasing crop yield by 20–40%	[49, 53, 57, 59]
Alternate wetting and drying (AWD)	Increases water productivity by 10–28% through reduction of water use up to 37% by allowing the soil to become periodically dry during the growing season without yield penalty	[10, 29, 37, 41, 49]
Direct Sowing of Rice (DSR)	Increases water productivity by 18–28% compared to puddled transplanted rice	[13, 32, 34, 42]
Drip and Sprinkler Irrigation	Decreases water footprint and increases yields by 42–48% saving of irrigation water Sprinkler irrigation decreases water footprint by saving irrigation water by 29–34%	[11, 48, 50, 52]

the levels decreased from 9.06 m in 2000–2001 to 17.31 m in 2018–2019 [36]. Both states receive low rainfall, with Punjab receiving 534 mm and Haryana receiving 687 mm. Despite the semi-arid steppe climate (Bwhw) [48], paddy has become the most important crop in both states, with a larger acreage compared to other major paddy-growing states. This is due to continued policy support, including procurement at pre-announced MSP and subsidies for irrigation and fertilizers. However, the increase in paddy acreage has led to accelerated groundwater extraction, with electricity policy regimes playing a crucial role in these states (Fig. 6). Overextraction of groundwater continued despite the Act mandating delay in paddy sowing until the onset of monsoon. The rate of overextraction is three times higher in Punjab than in Haryana.

Paddy cultivation needs only about 400–700 mm of water for meeting its evapotranspiration needs [9], thus the overexploitation of groundwater should not be attributed to paddy cultivation in the state. Although ground water is used for paddy cultivation in the state, but, over exploited ground water goes as wastage as paddy crop does not need such a huge water. The overexploitation of groundwater resources is primarily driven by state-sponsored free or subsidized electricity and large-scale procurement of paddy at pre-announced Minimum Support Prices (MSP). This system effectively insures farmers against price and market risks, thereby incentivizing them to extract groundwater resources beyond what is necessary for paddy cultivation. Over 90% of paddy output in Punjab and Haryana is purchased for the public distribution system and buffer stocking. The yield of paddy is significantly higher than other crops in both states, and farmers might perceive delayed paddy transplantation as a risk that could reduce their yield and that of subsequent crops.

Strategy for Reducing Water Consumption in Paddy

It is possible to cultivate rice using minimal water while maintaining its yield. To achieve water savings in rice cultivation, various strategies can be implemented, including optimal water scheduling, transitioning from puddled transplanted rice to direct seeding, employing mulching techniques, adopting micro irrigation, and selecting less water-dependent varieties.

Empirical evidence suggests that implementing the System of Rice Intensification (SRI) method may yield water savings of 25–73%, reduce water footprint and enhance paddy yield by 20–40% [51, 55]. Additionally, the Alternate Wetting and Drying (AWD) technique has been shown to increase water productivity of paddy by 10- 28%

while reducing water use by up to 37% [30, 38]. Furthermore, the practice of Direct Sowing of Rice (DSR) could enhance water productivity of paddy rice by 17.9–27.5%, maintaining yield on par with that of transplanted rice [13, 35, 43]. Moreover, the adoption of drip and sprinkler irrigation systems could save irrigation water by 42–48% and 29–34%, respectively, for paddy cultivation method [11, 50] (Table 5). Hence, through the adoption of improved cultivation and irrigation water management methods, the water footprint of paddy rice cultivation could be substantially reduced, consequently enhancing the water productivity of paddy.

To mitigate over-extraction of groundwater—particularly in Punjab and Haryana, where critical declines in water tables pose a serious threat—techniques such as AWD and DSR must be prioritized. Additionally, policymakers should introduce incentives, such as carbon credits, to encourage farmers to adopt these methods, given their potential to generate carbon credits.

In the Northern Region, specifically in Central Punjab, Haryana and Western Uttar Pradesh, as well as in the unbunded upland ecologies of Eastern states such as Odisha, West Bengal, Jharkhand, and Bihar, shifting from water-intensive paddy to alternative, water-efficient crops are essential. In the short term, this strategy could diversify around 1 million hectares of paddy area in the Northern Region and an additional 2 million hectares in the Eastern upland areas. With strategic policy support and scientific innovation, this diversification can be expanded over the long term. Conversely, in the bunded lowland areas of East India and the Northeastern states, the focus should remain on increasing paddy production sustainably. By adopting high-yielding rice varieties and efficient cultivation techniques such as Direct Seeded Rice (DSR), System of Rice Intensification (SRI), and Alternate Wetting and Drying (AWD), along with scientific interventions to enhance seedling vigour, weed competitiveness, and anaerobic germination for lowland ecologies, and introducing drought-tolerant and weed-competitive paddy varieties for upland ecologies, it is possible to enhance productivity while reducing the water footprint of paddy in these regions.

Conclusions

Efficient water management is crucial in ensuring the sustainable future of rice crop production in India, particularly within the context of climate change. A comprehensive understanding of green and blue water requirements, as well as water productivity, is important for the formulation of water-effective policies and practices in paddy cultivation. The observed variations in state-specific water footprint and productivity emphasize the critical need for tailored strategies to optimize water utilization across diverse regions. Regions characterized by surplus rainfall, such as the Northeastern states, present opportunities for sustainable rice crop production and should prioritize the implementation of water harvesting infrastructure. Conversely, Northern regions (e.g., Punjab and Haryana) heavily reliant on groundwater for irrigation face the imminent risk of depleting water tables. Moreover, climate factors (e.g., variability in precipitation, temperature, and humidity) directly affects irrigation demand and crop evapotranspiration, impacting the overall water footprint. In future climate change scenarios projected rising temperatures may lead to increased water demand, highlighting the importance of adaptive practices under climate change scenarios. Addressing this necessitates improved irrigation management and technological interventions such as AWD, DSR, sensor-based irrigation scheduling to reduce water footprint and enhance water productivity in paddy cultivation. DSR and AWD have the potential to generate carbon credits. Linking carbon credits to DSR and AWD methods for paddy cultivation can incentivize farmers to adopt these methods, thereby helping to reduce the water footprint of paddy production. Furthermore, the selection of duration of variety's (short or long) and the ecology (lowland, upland, or medium land) significantly impact the water footprint of paddy production. Sustainable water management practices not only serve to mitigate the impacts of climate change but also bolster climate resilience, thereby ensuring food security and aligning with the Sustainable Development Goals (SDGs).

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

[1] Alauddin M, Sharma BR (2013) Inter-district rice water productivity differences in Bangladesh: an empirical exploration and implications. Ecol Econ 93:210–218. https://doi.org/10.1016/j.ecolecon.2013.05.015

[2] Anika N, Filaini R, Cahyani D (2019) Water productivity analysis in irrigated central rice production area of Solok Regency, Indonesia. IOP Conf Ser Earth Environ Sci 355:012100. https://doi.org/10.1088/1755-1315/355/1/012100
[3] Anonymous (2023) Agricultural Statistics of Rajasthan, Year 2021–2022. https://rajas.rajasthan.gov.in/PDF/2202024124440PMAgriculturalStatistics.pdf. Accessed 20 June 2024
[4] Anonymous (2023) Third Advance Estimates of Area, Production & Productivity of Principal Crops during 2022–23 In MS https://krishi.maharashtra.gov.in/Site/Upload/GR/THIRD%20ADVANCE%20ESTIMATES%202022-23%20DISTRICTWISE%20CROPWISE.pdf. Accessed 15 June 2024
[5] Anonymous (2017) Agricultural statistics. https://mpkrishi.mp.gov.in/hindisite_New/APY2_12_05_2017.pdf. Accessed 15 June 2024
[6] AICRP on Sugarcane (2024) From Coordinator's Desk. Accessed 26 April 2024
[7] Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration: guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. FAO, Rome, Italy. https://www.researchgate.net/publication/235704197
[8] Bouman BAM, Tuong TP (2001) Field water management to save water and increase in productivity in irrigated lowland rice. Agric Water Manage 49:11–30. https://doi.org/10.1016/S0378-3774(00)00128-1
[9] Bouman B (2009) How much water does rice use? Water Manag 69:115–133
[10] Bwire D, Saito H, Mugisha M, Nabunya V (2022) Water productivity and harvest index response of paddy rice with alternate wetting and drying practice for adaptation to climate change. Water 14:3368. https://doi.org/10.3390/w14213368
[11] Cebi U, Ozer S, Ozturk O, Aydın B, Çakır R (2023) Yield and water productivity of rice grown under different irrigation methods. J Agric Sci 161:387–397. https://doi.org/10.1017/S0021859623000308
[12] Chapagain AK, Hoekstra AY (2011) The blue, green and grey water footprint of rice from production and consumption perspectives. Ecol Econ 70:749–758
[13] Chakraborty D, Ladha JK, Rana DS et al (2017) A global analysis of alternative tillage and crop establishment practices for economically and environmentally efficient rice production. Sci Rep 7:9342. https://doi.org/10.1038/s41598-017-09742-9
[14] Chapagain AK, Tickner D (2012) Water footprint: help or hindrance? Water Altern 5:563
[15] Chatterjee S, Stoy PC, Debnath M, Nayak AK, Swain CK, Tripathi R, Chatterjee D, Mahapatra SS, Talib A, Pathak H (2021) Actual evapotranspiration and crop coefficients for tropical lowland rice (*Oryza sativa* L.) in eastern India. Theor Appl Climatol 146:155–171. https://doi.org/10.1007/s00704-021-03710-0
[16] De Beer A (2016) Water use efficiency of soybeans. Soybean production. Monsanto. Water use efficiency of soybeans.pdf (arc.agric.za) (Accessed 13.06.2021)
[17] Debnath M, Sarangi A, Sena DR, Singh DK (2022) Validation of SWAT model using satellite-derived evapotranspiration data. Indian J Soil Conserv 50:137–146
[18] Debnath M, Sena DR, Sarangi A, Singh DK (2023) Variability of rainfall, temperature and evapotranspiration variables under climate change in five selected districts of central Punjab based on data derived from iitm-regcm4 based six model ensembles. Scientist 1:5149–5158. https://www.researchgate.net/publication/369037598
[19] Debnath M, Sena DR, Sarangi A, Singh DK (2023) Simulating the effect of increased area under direct seeded rice and canal water supply on ground water table under climate change in five selected central Punjab districts, India. Scientist 2:274–280. https://www.researchgate.net/publication/369037953
[20] Desai BB, Kotecha PM, Salunkhe DK (1999) Science and technology of groundnut: biology, production, processing and utilization. Naya Prokash, 677 p
[21] FAO (2024) Databases S& Software. https://www.fao.org/land-water/home/en/ Accessed 26 April 2024
[22] Gaur PM, Tripathi S, Gowda CLL, Ranga Rao GV, Sharma HC, Pande S, Sharma M (2010) Chickpea Seed Production Manual. International Crops Research Institute for the Semi-Arid Tropics, Andhra Pradesh, India. https://tropicallegumeshub.com/wp-content/uploads/2020/07/ChickpeaManual_full.pdf. Accessed 25 July 2024
[23] Giridhar S, Biswanath (2009) Mapping of evapotranspiration zones in India using GIS. International Conference of Water, Energy and Society (WEES-2009), New Delhi, 12–16 January 2009
[24] Government of India (2023) Annual report 2023–2024. https://agriwelfare.gov.in/Documents/AR_English_2023_24.pdf. Accessed 25 October 2024
[25] Haida C, Chapagain AK, Rauch W, Riede M, Schneider K (2019) From water footprint to climate change adaptation: capacity development with teenagers to save water. Land Use Policy 80:456–463
[26] Hembram P, Subudhi CR, Subudhi R (2020) Water and irrigation requirement for mustard (*Brassica*) crop of north central plateau zone of Odisha. J Bio Innov 9:1313–1321
[27] Hoekstra AY, Chapagain AK (2014) Water footprints of nations: water use by people as a function of their consumption pattern. Water Resour Manage 21:35–48. https://doi.org/10.1007/s11269-006-9039-x
[28] Hoekstra AY, Mekonnen MM (2012) The water footprint of humanity. Proc Natl Acad Sci 109:3232–3237
[29] Hoekstra AY, Chapagain AK, Aldaya MM, Mekonnen MM (2009) Water footprint manual. Water footprint network, Enschede, The Netherlands, pp 1–131
[30] Haonan Q, Jie W, Shihong Y, Zewei J, Yi X (2023) Current status of global rice water uses efficiency and water-saving irrigation technology recommendations. J Agron Crop Sci 209:734–746
[31] ICAR-CCARI (2010) Groundnut production. https://ccari.icar.gov.in/dss/groundnut.html. Accessed 26 April 2024
[32] ICAR-IIMR (2024) ICAR-Indian Institute of Maize Research. Seed Portal. Accessed 26 April 2024
[33] Ishfaq M, Akbar N, Anjum SA, Anwar-Ijl-Haq M (2020) Growth, yield and water productivity of dry direct seeded rice and transplanted aromatic rice under different irrigation management regimes. J Integr Agric 19:2656–2673
[34] Jain R, Kishore P, Singh DK (2019) Irrigation in India: status, challenges and options. J Soil Water Conserv 18:354–363
[35] Kaur J, Singh A (2017) Direct seeded rice: prospects, problems/constraints and researchable issues in India. Curr Agric Res J 5:13
[36] Kishore P, Roy D, Birthal PS, Srivastava SK (2024) Regulation, and Policy Response to Groundwater Preservation in India. Policy Paper 43, ICAR-National Institute of Agricultural Economics and Policy Research (NIAP), New Delhi
[37] Kumaraperumal R, Pazhanivelan S, Ragunath KP, Raman MG (2019) Mapping of rainfed areas in Tamil Nadu using remote sensing technology. Madras Agric J 106:643–646. https://doi.org/10.29321/MAJ2019.000324
[38] Kumar A, Nayak AK, Mohanty S, Das BS (2016) Greenhouse gas emission from direct seeded paddy fields under different soil water potentials in eastern India. Agric Ecosyst Environ 228:111–123

[39] Mahajan G, Kumar V, Chauhan BS (2017) Rice Production in India. In: Chauhan B, Jabran K, Mahajan G (eds) Rice Production Worldwide. Springer, Cham. https://doi.org/10.1007/978-3-319-47516-5_3
[40] Maiti A, Hasan MK, Sannigrahi S, Bar S, Chakraborti S, Mahto SS, Chatterjee S, Pramanik S, Pilla F, Auerbach J, Sonnentag O (2024) Optimal rainfall threshold for monsoon rice production in India varies across space and time. Commun Earth Environ 5:302. https://doi.org/10.1038/s43247-024-01414-7
[41] Mandal R, Jana K, Ghosh S, Biswas A, Bhadra KK, Mallick GK (2018) Production oriented survey (POS) on different aspects of rice cultivation and farmers practices under red and lateritic zone of West Bengal, India. Arch Agric Environ Sci 3:378–381. https://doi.org/10.26832/24566632.2018.030408
[42] Mboyerwa PA, Kibret K, Mtakwa PW, Aschalew A (2021) Evaluation of growth, yield, and water productivity of paddy rice with water-saving irrigation and optimization of nitrogen fertilization. Agronomy 11:1629. https://doi.org/10.3390/agronomy11081629
[43] Mohapatra KK, Nayak AK, Patra RK, Swain CK, Kumar A, Shahid M, Mohanty S, Tesfai M (2023) Multi-criteria assessment to screen climate smart rice establishment techniques in coastal rice production system of India. Front Plant Sci 14:1130545. https://doi.org/10.3389/fpls.2023.1130545
[44] Mohapatra T, Nayak AK, Raja R, Shahid M (2013) Vision 2050. Central Rice Research Institute.https://icar-nrri.in/wp-content/uploads/2019/08/ebook_crrivision2050_final_16Jan13.pdf. Accessed 20 June 2024
[45] Nag A, Adamala S, Raghuwanshi NS, Singh R, Bandyopadhyay A (2014) Estimation and ranking of reference evapotranspiration for different spatial scales in India. J Indian Water Resour Soc 34:35–45
[46] Nayak AK, Kumar A, Tripathi R, Panda BB, Mohanty S, Shahid M, Raja R, Khanam R, Bhaduri D, Satapathy BS, Lal B (2021) Improved Water Management Technologies for Rice Production System. NRRI Research Bulletin No. 32, ICAR-National Rice Research Institute, Cuttack, Odisha, India. pp 40
[47] Nayak AK, Tripathi R, Debnath M, Swain CK, Dhal B, Vijaykumar S, Nayak AD, Mohanty S, Shahid M, Kumar A, Rajak M (2023) Carbon and water footprints of major crop production in India. Pedosphere 33:448–462. https://doi.org/10.1016/j.pedsph.2022.06.045
[48] NCERT (2023) Climate, vegetation and soil. https://ncert.nic.in/ncerts/l/kegy104.pdf. Accessed 20 Oct 2024
[49] Pathak H, Tripathi R, Jambhulkar NN, Bisen JP, Panda BB (2020) Eco-regional-based rice farming for enhancing productivity, profitability and sustainability. NRRI Research Bulletin No. 22, ICAR-National Rice Research Institute, Cuttack, Odisha, India. pp 28. https://krishi.icar.gov.in/jspui/bitstream/123456789/31841/1/Eco-regional%20Rice%20farming.pdf
[50] Pinto MAB, Parfitt JMB, Timm LC, Faria LC, Concenço G, Stumpf L, Nörenberg BG (2020) Sprinkler irrigation in lowland rice: crop yield and its components as a function of water availability in different phenological phases. Field Crops Res 248:107714
[51] Ramesh T, Rathika S (2020) Evaluation of rice cultivation systems for greenhouse gases emission and productivity. Int J Ecol Environ Sci 2:49–54
[52] Rao KVR, Gangwar S, Keshri R, Chourasia L, Bajpai A, Soni K (2017) Effects of drip irrigation system for enhancing rice (Oryza sativa L.) yield under system of rice intensification management. Appl Ecol Environ Res 15:487–494. https://doi.org/10.15666/aeer/1504_487495
[53] Rittler L, Bykova O (2020) Water use and irrigation in soybean. https://zenodo.org/records/5865480
[54] Sharma BR, Gulati A, Mohan G, Manchanda S, Ray I, Amarsinghe U (2018) Water productivity mapping of major Indian crops. NABARD-ICRIER Report. pp 179. https://www.nabard.org/auth/writereaddata/tender/1806181128Water%20Productivity%20Mapping%20of%20Major%20Indian%20Crops,%20Web%20Version%20(Low%20Resolution%20PDF).pdf. Accessed 25 June 2024
[55] Thakur AK, Mohanty RK, Patil DU, Kumar A (2014) Impact of water management on yield and water productivity with system of rice intensification (SRI) and conventional transplanting system in rice. Paddy Water Environ 12:413–424
[56] Timsina J, Godwin D, Humphreys E, Kukal SS, Smith D (2008) Evaluation of options for increasing yield and water footprint of wheat in Punjab, India using the DSSAT-CSM-CERES-wheat model. Agric Water Manage 95:1099–1110
[57] TNAU Agritech Portal (2016) http://www.agritech.tnau.ac.in/. Accessed 26 April 2024
58. Tuong TP, Bouman BAM (2003) Rice production in water-scarce environments. Water Footpr Agric: Limits Oppor Improv 1:13–42
[59] Tong LA, Ulubaşoglu ML, Guven C (2022) Growing more rice with less water: the system of rice intensification and water productivity in Vietnam. Aust J Agric Resour Econ 66(3):581–611. https://doi.org/10.1111/1467-8489.12477
[60] Upadhyaya A (2018) Rice and wheat water productivity assessment in India. MOJ Ecol Environ Sci 3:426–432. https://doi.org/10.15406/mojes.2018.03.00124
[61] Vittal KPR, Sinha PK, Ravindra Chary G, Maruthi Sankar GR, Srijaya T, Ramakrishna YS, Samra JS, Singh G (eds) (2004) District wise Promising Technologies for Rainfed Rice based Production System in India. All India Coordinated Research Project for Dryland Agriculture, Central Research Institute for Dryland Agriculture, Indian Council of Agricultural Research, Hyderabad. pp 114. https://www.icar-crida.res.in/assets/img/Books/2004-05/Rice.pdf. Accessed 20 June 2024