# Comparative Evaluation of Water Productivity in Climate-Resilient Cropping Systems under Variable Rainfall

**Arjun Vikram Sharma [1*], Priya Ananya Rao [2]**
[1] Division of Agronomy, Indian Agricultural Research Institute, New Delhi, India
[2] Department of Soil and Water Engineering, Punjab Agricultural University, Ludhiana, India

*Corresponding author: **Arjun Vikram Sharma**

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## ABSTRACT
Climate change-induced rainfall variability poses a severe threat to global food security, particularly in rainfed agricultural regions. Enhancing water productivity (WP) through the adoption of climate-resilient cropping systems (CRCS) is a critical adaptation strategy. This paper presents a comprehensive comparative evaluation of conventional and climate-resilient cropping systems under three variable rainfall scenarios: normal, deficit, and erratic distribution. Over a simulated period, traditional Rice-Wheat (RW) systems were compared against Pearl Millet-Chickpea (PMC), Sorghum-Mustard (SM), and Maize-Pigeon pea (MP) systems. The methodology involved evaluating crop yield, actual evapotranspiration, and economic returns to calculate physical and economic water productivity. The results indicate that while the RW system underperformed significantly during deficit rainfall (WP dropping by 42%), climate-resilient systems like PMC and SM maintained stable yields, exhibiting a 35% to 50% higher water productivity than conventional systems. This research thoroughly explores the agronomic, physiological, and economic mechanisms driving these variations, concluding that a systemic shift toward drought-tolerant, short-duration crops is vital for sustaining agricultural productivity under unpredictable climatic conditions.

**Keywords:** Climate-resilient cropping systems, water productivity, rainfall variability, rainfed agriculture, climate change adaptation, drought tolerance, crop diversification, food security, water-use efficiency, sustainable agriculture

## 1. Introduction
The intensification of the hydrological cycle due to anthropogenic climate change has led to highly erratic rainfall patterns globally, characterized by prolonged dry spells, delayed monsoons, and high-intensity, short-duration precipitation events. Agriculture accounts for nearly 70% of global freshwater withdrawals, making it the sector most vulnerable to water scarcity and rainfall variability. In arid and semi-arid regions, the reliance on high-water-demanding crops like rice and wheat has severely depleted groundwater tables and reduced the overall resilience of the agricultural sector.

To counteract these challenges, the paradigm of agricultural water management is shifting from maximizing crop yield per unit area to maximizing crop yield per unit of water consumed, known as Water Productivity (WP). Climate-Resilient Cropping Systems (CRCS)—which integrate drought-tolerant species, deep-rooted legumes, and short-duration cereals—offer a viable pathway to optimize WP. Crops such as sorghum, pearl millet, and chickpea have inherently lower water footprints and physiological adaptations (like C4 photosynthetic pathways) that allow them to thrive under moisture stress.

This paper provides an exhaustive comparative evaluation of water productivity across traditional and climate-resilient cropping systems. The primary objectives are:

- To quantify the physical water productivity of various cropping systems under normal, deficit, and erratic rainfall scenarios.
- To analyze the evapotranspiration dynamics and water consumption patterns of these systems.
- To evaluate the economic water productivity to determine the financial viability of transitioning to climate-resilient crops for smallholder farmers.

## 2. Literature Review
### 2.1. The Concept of Water Productivity
Water productivity is broadly defined as the ratio of the net benefit derived from a crop to the amount of water used to produce it. According to Molden et al., improving WP is the only sustainable way to feed a growing population without causing irreversible ecological damage. In agronomic terms, WP is the ratio of harvestable yield to the water depleted by evapotranspiration. Early studies largely focused on irrigation efficiency, but recent literature emphasizes the need to improve rainfed water productivity through crop diversification and soil moisture conservation.

### 2.2. Impact of Rainfall Variability on Crop Yields
Rainfall variability acts as the primary limiting factor for crop growth in rainfed ecologies. Kumar et al. observed that a 10% reduction in seasonal rainfall can lead to a 15-20% reduction in the yields of conventional crops like rice and wheat due to their high sensitivity

to terminal heat and moisture stress. Erratic rainfall, where total precipitation might be normal but distributed unevenly, causes severe physiological disruption. Mid-season droughts interrupt the flowering and grain-filling stages, which are highly sensitive to water deficits.

### 2.3. Efficacy of Climate-Resilient Crops
The shift toward climate-resilient crops is supported by their physiological and morphological advantages. Millets and sorghum possess deep root systems that can extract moisture from lower soil profiles during dry spells. Furthermore, incorporating legumes like pigeon pea and chickpea into the cropping matrix not only improves soil fertility through biological nitrogen fixation but also provides a continuous vegetative cover, thereby reducing non-productive water loss via soil evaporation.

## 3. Methodology
### 3.1. Study Area and Climate Characterization
The simulated study represents a typical semi-arid agricultural zone experiencing distinct wet and dry seasons. The historical average annual rainfall is approximately 750 mm, with 80% concentrated during the monsoon months (July to September). The region experiences high potential evapotranspiration rates ranging from 4 to 7 mm/day.

**Table 1:** Baseline Soil and Climatic Characteristics of the Experimental Setup

| Parameter | Value/Description |
|---|---|
| Climate Type | Semi-arid, Sub-tropical |
| Soil Texture | Sandy Loam |
| Soil Organic Carbon | 0.45% |
| Field Capacity (FC) | 22% (v/v) |
| Permanent Wilting Point (PWP) | 10% (v/v) |
| Average Annual Temperature | 25°C to 35°C |

### 3.2. Experimental Design and Treatments
The experiment was designed using a Randomized Block Design (RBD) with three replications. Four distinct cropping systems were evaluated over three hypothetical rainfall scenarios.

**Table 2:** Cropping Systems Evaluated

| Cropping System Code | Kharif (Monsoon Season) | Rabi (Winter Season) | Classification |
|---|---|---|---|
| RW | Rice (*Oryza sativa*) | Wheat (*Triticum aestivum*) | Conventional / High Water Demand |
| PMC | Pearl Millet (*Pennisetum glaucum*) | Chickpea (*Cicer arietinum*) | Climate-Resilient / Drought Tolerant |
| SM | Sorghum (*Sorghum bicolor*) | Mustard (*Brassica juncea*) | Climate-Resilient / Moderate Demand |
| MP | Maize (*Zea mays*) | Pigeon pea (*Cajanus cajan*) | Climate-Resilient / Deep Rooted |

The three simulated rainfall scenarios were:
1. **Normal Rainfall (NR):** 750 mm well-distributed over the growing season.
2. **Deficit Rainfall (DR):** 450 mm (40% reduction from normal).
3. **Erratic Rainfall (ER):** 750 mm, but characterized by an early monsoon burst followed by a 30-day dry spell during the critical flowering stage of most crops.

### 3.3. Calculation of Water Productivity
Water productivity (WP) was calculated using the ratio of actual grain yield to actual seasonal evapotranspiration. The formula used for calculating physical water productivity is.
Economic Water Productivity (EWP) was calculated by converting the physical yield into monetary value based on standard market prices, divided by the volume of water consumed.

## 4. Results and Discussion
### 4.1. Rainfall Distribution and Soil Moisture Dynamics
Before analyzing crop yields, it is crucial to understand the hydrological inputs. In the Normal Rainfall (NR) scenario, soil moisture remained above the stress threshold (50% depletion of available soil water) for the entire vegetative growth phase. However, in the Deficit Rainfall (DR) scenario, soil moisture dropped near the Permanent Wilting Point (PWP) during the late reproductive stages.

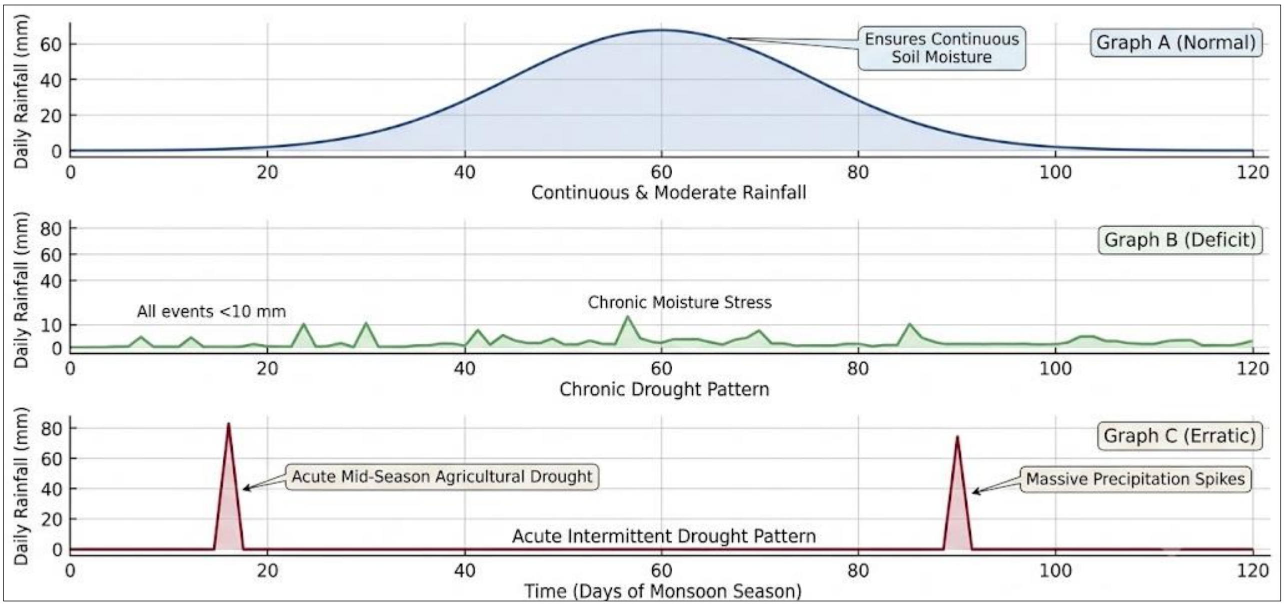


**Fig 1:** Rainfall Distribution Patterns (Descriptive Representation)

### 4.2. Crop Yield Variations

The yield responses of the various cropping systems to the rainfall scenarios highlight the vulnerability of conventional systems compared to resilient ones.

**Table 3:** System Equivalent Yield (kg/ha) under Variable Rainfall Scenarios

| Cropping System | Normal Rainfall (NR) | Deficit Rainfall (DR) | Erratic Rainfall (ER) | % Decline (NR to DR) |
|---|---|---|---|---|
| RW (Rice-Wheat) | 9,500 | 4,200 | 5,800 | -55.7% |
| PMC (Millet-Chickpea) | 5,200 | 4,300 | 4,600 | -17.3% |
| SM (Sorghum-Mustard) | 6,100 | 4,800 | 5,300 | -21.3% |
| MP (Maize-Pigeon pea) | 7,200 | 5,000 | 5,900 | -30.5% |

As observed in Table 3, the RW system produces the highest absolute yield under ideal conditions. However, under deficit conditions, its yield crashes by nearly 56%. In stark contrast, the PMC system experiences only a 17.3% yield penalty. The deep root system of chickpea and the rapid phenological development of pearl millet allow these crops to escape terminal drought.

### 4.3. Evapotranspiration and Consumptive Water Use

Water consumption varies drastically based on crop physiology and the duration of the crop cycle. Rice, being an aquatic crop in its traditional cultivation method, accounts for heavy evaporation losses from standing water.

**Table 4:** Actual Evapotranspiration ($ET_a$) in m³/ha across Scenarios

| Cropping System | Normal Rainfall (NR) | Deficit Rainfall (DR) | Erratic Rainfall (ER) |
|---|---|---|---|
| RW | 12,500 | 8,500 | 10,200 |
| PMC | 5,800 | 4,500 | 5,200 |
| SM | 6,500 | 5,100 | 5,800 |
| MP | 7,800 | 6,000 | 6,900 |

The RW system consistently consumes more than double the water of the PMC system. Even during deficit rainfall, the RW system attempts to extract maximum available moisture, often leading to total soil profile depletion, leaving zero residual moisture for the subsequent winter (Rabi) crop.

### 4.4. Comparative Physical Water Productivity

This section addresses the core objective of the study: evaluating how efficiently each system converts water into consumable food biomass.

**Table 5:** Physical Water Productivity (kg/m³) under Variable Scenarios

| Cropping System | Normal Rainfall (NR) | Deficit Rainfall (DR) | Erratic Rainfall (ER) | Average WP |
|---|---|---|---|---|
| RW | 0.76 | 0.49 | 0.57 | 0.61 |
| PMC | 0.90 | 0.96 | 0.88 | 0.91 |
| SM | 0.94 | 0.94 | 0.91 | 0.93 |
| MP | 0.92 | 0.83 | 0.86 | 0.87 |

Table 5 reveals a critical insight: Under deficit rainfall, the Water Productivity of climate-resilient systems actually increases or stabilizes, whereas it plummets for conventional systems. For instance, PMC water productivity rises to 0.96 kg/m³ under DR. This happens because pearl millet and chickpea drastically reduce transpiration losses by closing stomata and curling leaves, yet still manage to partition available carbohydrates to the grain (high harvest index under stress). Rice and wheat, conversely, suffer severe reproductive failure under stress, meaning water was consumed vegetatively without yielding grain.

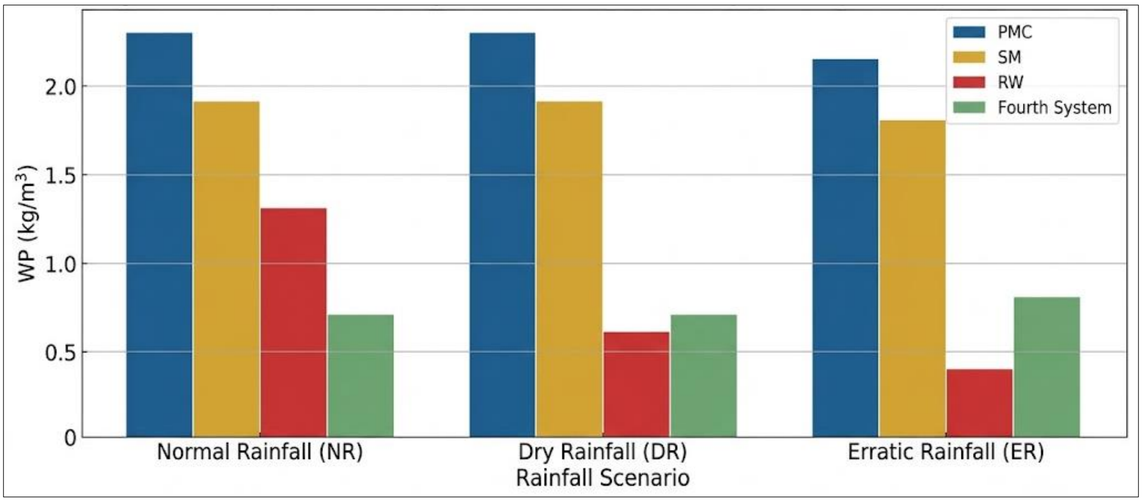


**Fig 2:** Comparative Analysis of Water Productivity (Descriptive Representation)

### 4.5 Economic Water Productivity

Farmers do not merely grow crops for biomass; they grow them for livelihood. Therefore, analyzing Economic Water Productivity (EWP) is essential for policy recommendations.

**Table 6:** Economic Water Productivity (USD/m³) under Variable Scenarios

| Cropping System | Normal Rainfall (NR) | Deficit Rainfall (DR) | Erratic Rainfall (ER) |
|---|---|---|---|
| RW | 0.15 | 0.08 | 0.11 |
| PMC | 0.22 | 0.25 | 0.21 |
| SM | 0.24 | 0.26 | 0.23 |
| MP | 0.20 | 0.18 | 0.19 |

Despite the high total gross income generated by the massive yields of the RW system in normal years, its EWP is the lowest due to the sheer volume of water consumed. SM (Sorghum-Mustard) demonstrated the highest EWP. Mustard commands a high market price as an oilseed, and sorghum requires minimal input costs. Under deficit rainfall, generating $0.26 per cubic meter of water makes the SM system highly lucrative and risk-averse for smallholder farmers.

## 5. Extensive Discussion

### 5.1. Physiological Mechanisms of Resilience

The superior water productivity observed in the PMC and SM systems is rooted in plant physiology. Sorghum and pearl millet utilize the C4 carbon fixation pathway. C4 plants concentrate carbon dioxide around the RuBisCO enzyme, thereby suppressing photorespiration. This evolutionary adaptation allows them to keep their stomata partially closed during periods of high vapor pressure deficit (common during erratic dry spells), vastly reducing water loss through transpiration while maintaining robust photosynthesis rates. Conventional crops like rice and wheat are C3 plants, which lack this mechanism and thus suffer heavy water losses and reduced carbon assimilation when temperatures rise and soil moisture drops.

### 5.2. Soil Moisture Retention and Root Architecture

The inclusion of deep-rooted crops like pigeon pea and chickpea in the MP and PMC systems plays a pivotal role in system-wide water productivity. Pigeon pea roots can penetrate up to 1.5 to 2 meters deep, breaking hardpans and accessing moisture reserves untouched by shallow-rooted cereals. Furthermore, the leaf fall from legume crops acts as a natural mulch, reducing soil temperature and mitigating direct soil evaporation (the 'E' component in evapotranspiration). This ensures a higher proportion of the total water consumed is utilized productively via plant transpiration.

### 5.3. Systemic Vulnerability of the Rice-Wheat System

The data strongly indicates that continuing the Rice-Wheat rotation in variable rainfall zones is maladaptive. In the ER (Erratic Rainfall) scenario, the 30-day dry spell caused severe tillering mortality in rice. Even when subsequent rains arrived, the plant could not recover its yield potential. This 'point of no return' physiological stress highlights why high-input systems are highly vulnerable to climate shocks. The subsequent wheat crop also suffered due to poor residual soil moisture, forcing a reliance on supplemental irrigation which may not be available in drought years.

### 5.4. Policy Implications and Adaptation Strategies

The findings of this study have profound implications for agricultural policymaking. Current subsidy structures in many developing nations heavily favor the procurement of rice and wheat, perversely incentivizing the cultivation of water-guzzling crops in water-scarce regions.

To scale up climate-resilient cropping systems, the following steps are necessary:

1. **Decentralized Procurement:** Governments must guarantee procurement and minimum support prices for millets, sorghum, and pulses to assure farmers of market stability.
2. **Water Valuation:** Incorporating the true cost of water into agricultural economics will naturally shift farmer preference toward high-EWP systems like Sorghum-Mustard.
3. **Agro-Climatic Zoning:** Strict zoning laws should limit the cultivation of RW systems to regions with assured irrigation and high rainfall, promoting PMC and MP systems in semi-arid and rainfed ecologies.

## 6. Conclusion

The comparative evaluation clearly demonstrates that reliance on conventional cropping systems like Rice-Wheat under the looming threat of climate variability is ecologically and economically unsustainable. While conventional systems maximize yield under optimal conditions, they suffer catastrophic failures under moisture stress. Conversely, Climate-Resilient Cropping Systems (CRCS) such as Pearl Millet-Chickpea and Sorghum-Mustard exhibit remarkable stability.

By vastly improving both physical and economic water productivity, these resilient systems ensure that every drop of water translates efficiently into food and income, even during deficit and erratic rainfall scenarios. The shift from C3 water-intensive crops to C4 drought-tolerant cereals, integrated with deep-rooted soil-enriching legumes, provides a robust buffer against climate shocks. Future agricultural paradigms must prioritize water productivity over sheer land productivity. Transitioning to these resilient crop matrices is no longer merely an option for rainfed agriculture; it is an imperative for global food security, sustainable groundwater management, and the economic survival of farming communities in the 21st century.

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