PLANT SCIENCE TODAY
Vol 13(sp1): 1-10
https://doi.org/10.14719/pst.11049

eISSN 2348-1900

RESEARCH ARTICLE

# Real-time contingency measures for coping with agricultural drought in semi-arid vertisols of southern Tamil Nadu, India

**B Bhakiyathu Saliha[1*], M Manikandan[1], V Sanjivkumar[1], M Joseph[1], K A Gopinath[2] & J V N S Prasad[2]**

[1]ICAR-All India Coordinated Research Project for Dryland Agriculture, Agricultural Research Station, Tamil Nadu Agricultural University, Kovilpatti 628 501, Tamil Nadu, India
[2]ICAR-Central Research Institute for Dryland Agriculture, Hyderabad 500 059, Telangana, India

*Correspondence email - bhakiyathusaliha@tnau.ac.in

Received: 02 August 2025; Accepted: 16 December 2025; Available online: Version 1.0: 13 February 2026

**Cite this article:** Bhakiyathu BS, Manikandan M, Sanjivkumar V, Joseph M, Gopinath KA, Prasad JVNS. Real-time contingency measures for coping with agricultural drought in semi-arid vertisols of southern Tamil Nadu, India. Plant Science Today. 2026; 13(sp1): 1-10. https://doi.org/10.14719/pst.11049

## Abstract

Rainfed agriculture in semi-arid regions is increasingly threatened by climate change-induced rainfall deficits and erratic dry spells, especially during critical crop stages such as establishment, flowering and maturity. These weather anomalies often extend over 2–3 weeks, significantly reducing the crop yields and threatening farmers' livelihoods. In response, real-time contingency measures (RTCM) have been introduced as a micro-level adaptive strategy to combat drought and flood events through timely and site-specific interventions. The present study conducted over five cropping seasons (2019–2024) evaluated the effectiveness of RTCM in vertisols under rainfed cultivation of drought-tolerant Sorghum K12, a short-duration climate-resilient variety. The study systematically assessed dryness and wetness periods using the rainfall-to-pan evaporation ratio and categorizing drought episodes into early, mid and terminal stages. In response to these temporal stresses, a set of climate-resilient technologies was implemented, including resowing, *in-situ* moisture conservation through ridge-furrow planting, closure of deep soil cracks with crop residues as mulches and foliar sprays of KCl and $ZnSO_4$ to alleviate plant water stress. These interventions were triggered by real-time observations of soil moisture and rainfall variability. In this study, Percent Available Soil Moisture (PASM) was used as a key indicator to assess soil moisture availability, monitor agricultural drought, evaluate crop moisture stress and justify crop survival, which also supports the timely implementation of RTCM. Over the five-year period, grain yield increased by an average of 45.6 % with an annual increase ranging from 30.2 % to 58.9 % under RTC treatments compared to the control. Rainwater productivity improved significantly, ranging from 0.54 to 0.65 kg/m$^3$ and the benefit-cost ratio (B:C) increased from 2.02 to 3.06, underscoring the economic viability of the RTCM. Biomass yield and harvest index were significantly higher under RTCM, with LSD values confirming statistical significance at 5 % level. Notably, yield stability was achieved even during low-rainfall years such as 2022–23, demonstrating the effectiveness of adaptive drought management strategies. The findings confirm that RTCM offers a robust framework to minimize drought-induced yield losses, enhance soil moisture retention and ensure profitability in vertisol-based rainfed systems of southern Tamil Nadu.

**Keywords:** dryness; PASM; rainfed; sorghum; soil moisture

## Introduction

Agriculture forms the backbone of India's economy and food security, supporting nearly 48 % of the population and contributing approximately 15 % to the national GDP (1). Globally, India has the largest area under rainfed cultivation, with about 79.44 million hectares, nearly 57 % of the total cultivated land relying solely on rainfall (2). These regions contribute around 44 % of the country's food grain production and play a critical role in the cultivation of coarse cereals, pulses, oilseeds and cotton. Rainfed systems also support 80 % of horticultural crops and 60 % of livestock production, making them imperative to both food and livelihood security in rural India (3).

However, the productivity of rainfed agriculture is highly vulnerable to climate change, particularly the quantity, timing and distribution of rainfall. It is not merely the seasonal total rainfall but the intra-seasonal variability, such as dry spells during the critical crop stages that have a profound impact on crop establishment, growth and yield (4, 5). Irregular rainfall patterns can lead to soil moisture deficits resulting in water stress, reduced productivity and crop failure (6). Therefore, continuous monitoring of rainfall distribution and soil moisture dynamics is essential for enhancing the resilience and sustainability of rainfed agricultural systems.

While total seasonal rainfall is important, its distribution, particularly the occurrence of dry spells, plays a more critical role in influencing crop productivity (4). A dry spell is defined as a period of consecutive dry days with rainfall below a threshold value (7, 8). These intra-seasonal rainfall interruptions are especially critical in rainfed agriculture, as they often coincide with key crop growth stages and exacerbate moisture stress, affecting yields (9). Dry spell analysis thus becomes an essential tool for water resource planning and minimizing agricultural and socioeconomic losses.

Soil moisture, which closely correlates with rainfall variability in a non-linear manner, is a critical parameter in assessing dryness and agricultural drought (10). Reduced soil moisture during the monsoon period can induce dry conditions and negatively impact rainfed crops (11). Moisture stress during critical phenological stages such as flowering, pollination and grain filling is particularly detrimental to crop yields, especially in sorghum (12). Therefore, assessing soil moisture availability is imperative for understanding crop response under rainfed conditions.

Percent Available Soil Moisture (PASM) is a reliable indicator used to assess soil moisture availability and to monitor agricultural drought. It effectively reflects the extent of crop moisture stress and provides insight into the likelihood of crop survival under varying soil moisture regimes (13, 14). The Government of India has formally included PASM as a criterion in the Drought Declaration Protocol (15). PASM, based on soil water balance approaches, enables timely decisions in drought management and supports real-time contingency planning (16).

Rainfed agriculture in India is inherently vulnerable due to smallholder dominance and diverse agro-ecological conditions. This vulnerability is further exacerbated by climatic aberrations such as delayed monsoons, mid-season dry spells and erratic rainfall distribution. In response, real-time contingency measures (RTCM) have emerged as essential tools to mitigate the impact of weather extremes on agriculture. RTCMs are dynamic, location-specific agronomic interventions such as re-sowing, gap filling, crop diversification, foliar nutrition and moisture conservation implemented in real time based on current weather conditions and crop growth stages. These measures are crucial in minimizing yield losses, stabilizing farm income and improving moisture use efficiency under rainfed conditions (17).

To institutionalize these interventions, the All India Coordinated Research Project for Dryland Agriculture (AICRPDA) and ICAR - Central Research Institute for Dryland Agriculture (CRIDA) have developed location-specific crop contingency plans. These plans provide guidance for handling various weather-induced stress scenarios, including delayed onset of monsoon, mid-season droughts and excess rainfall, through a combination of crop management, water resource strategies and policy interventions (18–20). The successful implementation of RTCM has proven to be effective in enhancing the resilience of dryland farming systems.

Sorghum is a key dryland cereal grown under rainfed conditions in Tamil Nadu, particularly in semi-arid regions such as Dharmapuri, Salem, Namakkal and parts of Thoothukudi and Virudhunagar districts, where the Northeast Monsoon is the primary source of rainfall. Sorghum, a hardy C4 crop with high photosynthetic efficiency, thrives under drought and heat stress, making it ideal for rainfed agricultural systems. It is valued for its adaptability to low and erratic rainfall, heat tolerance and ability to perform well in marginal soils. Sorghum is cultivated on approximately 8 million hectares across India, with around 2.2 lakh hectares in Tamil Nadu. Beyond its role as a staple grain, it also serves as an important fodder crop, supporting integrated farming systems. Its deep root system and moisture-efficient physiology make it highly suited to dryland farming. With rising climate variability, promoting sorghum cultivation through improved varieties and water-conserving agronomic practices can enhance yield stability and improve the livelihoods of rainfed farmers in the region.

This study aims to assess the extent of dryness and agricultural drought using rainfall analysis and soil moisture indicators, with a focus on PASM. It further evaluates the effectiveness of RTCM in improving the crop performance and yield stability of rainfed sorghum grown on vertisols in Tamil Nadu. The study seeks to provide a scientific framework for monitoring drought and implementing adaptive strategies to enhance resilience, improve water use efficiency and support decision-making in rainfed agricultural systems.

## Materials and Methods

### Location of experimental field and climate details

The field experiments were conducted over five consecutive years (2019–20 to 2023–24) during the rabi season (October–December) and were subsequently continued through the winter season (January–February) at the Agricultural Research Station, Kovilpatti, situated in the Thoothukudi district of Tamil Nadu, India. Kovilpatti is a key location for rainfed agriculture and is well recognized for its ability to grow a range of semi-arid crops under challenging conditions, making it an ideal site for this study. It is situated at a latitude of 9°10′2.69″ N, a longitude of 77°52′36.29″ E and an average elevation of 90 m above mean sea level. The agro-climatic region of Kovilpatti falls under a semi-arid tropical climate. The long-term average annual rainfall is 720.2 mm, with the Northeast Monsoon contributing nearly 389 mm of total precipitation. The annual maximum and minimum mean daily temperatures are 35 °C and 22.9 °C respectively. The mean annual relative humidity stands at about 79 %, while the annual mean duration of sunshine is nearly 7.1 hr per day. The mean annual evaporation rate varies from 7 to 8 mm per day and the annual mean daily wind velocity is about 9 km/hr (21).

### Basic soil properties

The experimental site is located in Kovilpatti, a region predominantly covered by vertisols, which account for nearly 70 % of the total area in the Thoothukudi district of southern Tamil Nadu. Taxonomically, these soils are classified under the USDA system as fine, smectitic, isohyperthermic Typic Haplusterts (22). Soil type was identified through field survey and validated using standard soil classification criteria. The soil depth typically ranges from 110 cm to 150 cm. During periods of soil moisture stress, deep and wide cracks at least 1 cm in width and extending more than 50 cm in depth frequently develop in the soil. The physical and chemical properties of the soil of the

**Table 1.** Soil properties of the experimental field

| **A) Physical properties** | | | **B) Chemical properties** | | |
|---|---|---|---|---|---|
| a) | Texture | Clayey | a) | pH | 7.92 |
| b) | Depth | 190–200 cm | b) | EC | 0.19 dS $m^{-1}$ |
| c) | Field capacity | 35 % | c) | Available N | 135 kg $ha^{-1}$ |
| d) | Wilting point | 14 % | d) | Available P | 11.5 kg $ha^{-1}$ |
| e) | Bulk density | 1.33 kg $m^{-3}$ | e) | Available K | 360 kg $ha^{-1}$ |
| f) | Infiltration rate | 9 mm $hr^{-1}$ | f) | Organic carbon | 2.5 g $kg^{-1}$ |

experimental field are presented in Table 1.

The field trial comprised two treatments: $T_1$: Management of the crop during dry spell (real-time contingency measures) and $T_2$: Control (without real-time contingency measures). The area of each experimental plot was 2000 $m^2$. TNAU released sorghum variety K12 was cultivated with a seed rate of 15 kg/ha. The recommended fertilizer dose for rainfed conditions on vertisol soil was 40 kg N: 20 kg $P_2O_5$: 0 kg $K_2O$ per hectare. Fertilizers were applied using urea and a single superphosphate as sources of N and P. A total of 87 kg urea/ha and 125 kg SSP/ha were applied, with phosphorus as basal and nitrogen in two equal splits (basal and 30 days after sowing (DAS)). Potassium application was omitted due to the high inherent K fertility of the vertisol soil.

For conserving soil moisture *in situ*, ridges and furrows were constructed at 45 cm spacing, extending 10 m in length with the help of a ridger. The seeds were manually dibbled at a depth of 3–5 cm, placed two-thirds up the ridge, to maintain a row-to-row spacing of 45 cm and seed-to-seed spacing of 15 cm. Standard agricultural practices and crop protection measures were followed according to the guidelines of the Crop Production Guide of the State Department of Agriculture (23).

## Soil sampling

Soil water content (SWC) is widely recognized as one of the most critical factors influencing plant growth and development (24). Even slight variations in soil moisture can significantly affect crop productivity, particularly under dryland or water-limited conditions (25). To monitor SWC during the cropping period, soil samples were collected at weekly intervals throughout the growing season. Sampling was conducted from three soil depths: 0–15 cm, 15–30 cm and 30–45 cm. These samples were collected at the beginning of each week, irrespective of rainfall occurrence. The gravimetric method was employed to determine the SWC (26). This method involves weighing soil samples before and after oven-drying to calculate the SWC. The SWC ($\theta_m$) was calculated using Eqn. 1.

$$\text{Soil water content (\%)} = \frac{W_f - W_d}{W_d} \times 100 \qquad \text{(Eqn. 1)}$$

where $W_f$ = fresh weight of the soil sample and $W_d$ = dry weight of the soil sample.

SWC on a volumetric basis ($\theta_v$) was computed by multiplying the gravimetric SWC with the bulk density of the soil. This conversion provides a more accurate representation of the actual volume of water present in a given volume of soil, which is critical for assessing soil moisture availability for plant roots. Soil moisture within the root zone plays a key role in mitigating the adverse effects of drought on crop yield (27). Building on this, the root zone water content in the present study was estimated as the cumulative sum of ($\theta_v$) across all sampled depths, each weighted by the corresponding depth of the soil layer. The calculation was performed using Eqn. 2.

$$\mathrm{Wrz} = \theta_{v1}d_1 + \theta_{v2}d_2 + \theta_{v3}d_3 \qquad \text{(Eqn. 2)}$$

where $\theta_{v1}$, $\theta_{v2}$ and $\theta_{v3}$ are volumetric water contents at soil depths representing the root zone and $d_1$, $d_2$ and $d_3$ corresponding to the thickness of the soil layer sampled.

## Assessment of dryness and wetness

A dry day is typically defined as a day receiving an insignificant amount of rainfall, specifically less than 1 mm (28, 29). In contrast, a dry spell refers to an extended period of consecutive dry days with little to no rainfall. During the cropping season, the atmospheric evaporative demand generally ranges from 30 mm/week, which is common during the active rainy period, to around 40 mm/week at the onset of the season. When weekly rainfall amounts to only 20 mm, it meets merely 0.5 to 0.75 times the weekly evaporative demand. Therefore, in this agro-climatic context, a week receiving less than 20 mm of rainfall can be categorized as a dry week (30). Such dry weeks often expose crops to water stress, compelling them to rely on stored soil moisture to meet their water requirements. However, when dry spells persist for two or more consecutive weeks, the resulting soil moisture deficit can severely affect crop growth and significantly reduce yields (5). Hence, dry spells serve as important indicators of moisture stress and must be closely monitored to enable timely implementation of contingency measures.

In this study, dry spells were assessed using the rainfall to evaporation (R/E) ratio, a commonly used metric for evaluating agricultural water stress. An R/E ratio of less than 0.5 typically signifies dry conditions or a dry spell, a ratio between 0.5 and 1.5 indicates normal conditions and values above 1.5 suggest wet conditions. Weekly rainfall and evaporation data during the crop-growing period from 2019 to 2023 were analyzed to calculate dry spells based on this ratio.

## Estimation of agricultural drought based on percent available soil moisture (PASM)

PASM is a critical indicator for monitoring crop failure, as it reflects the amount of water in the soil that is available for plant uptake. PASM is derived from two key soil moisture parameters: field capacity (FC), the maximum amount of water the soil can hold after excess water has drained and the permanent wilting point (PWP), the moisture level below which plants can no longer extract water. The range between FC and PWP defines the plant-available water, which represents the soil moisture fraction that supports crop growth. When PASM falls below a specific threshold, it indicates that plants are under water stress, potentially leading to reduced physiological function, impaired development and ultimately, crop failure. Due to its relevance in capturing real-time soil moisture deficits, PASM is widely used as an indicator in the declaration of agricultural drought (14). In accordance with the Drought Manual issued by the Ministry of Agriculture and Farmers' Welfare, Government of India, weekly or crop stage-wise PASM was computed from observed soil moisture data using Eqn. 3.

$$\text{PASM (\%)} = \frac{\text{SMC-PWP}}{\text{FC-PWP}} \times 100 \qquad \text{(Eqn. 3)}$$

where SMC = weekly calculated volumetric soil moisture (vol./vol.) for the current week; PWP = permanent wilting point of soil (vol./vol.); FC = field capacity of the soil (vol./vol.). SMC measured at three depths, such as 0 to 15 cm, 15 to 30 cm and 30 to 45 cm, was used to calculate PASM values. These values were

**Table 2.** Agricultural drought classification based on PASM values

| Sl. No. | PASM | Agricultural drought |
|---|---|---|
| 1 | 76 %–100 % | No drought |
| 2 | 51 %–75 % | Mild drought |
| 3 | 26 %–50 % | Moderate drought |
| 4 | < 25 % | Severe drought |

then used to classify the intensity of agricultural drought throughout the study period. The corresponding classifications are presented in Table 2.

### Real-time contingency measures (RTCM) for various climate aberrations

RTCMs are designed to enhance resilience and sustain agricultural productivity under variable and extreme weather conditions. The primary objectives of RTCMs are (i) to facilitate timely crop establishment with an optimum plant population under delayed monsoon onset and (ii) to mitigate the adverse impacts of seasonal droughts, whether early, mid-season, or terminal, along with other extreme climatic events. These measures aim to improve crop performance, enhance water and nutrient use efficiency, increase productivity and ultimately improve farm income. The core components of RTCM implementation for coping with climatic aberrations include rainwater management (both *in-situ* and *ex-situ* conservation), selection of suitable crops and varieties, diversified cropping systems, appropriate nutrient management strategies and alternate land use planning (19, 31–33).

In the present study, RTCMs were implemented based on two key indicators: dryness index, defined as the ratio of rainfall to potential evaporation (P/E) and PASM values. These parameters served as early warning signals to guide location-specific interventions during weather aberrations. Table 3 presents the set of RTCMs implemented during various weather abnormalities.

### Estimation of rainwater productivity (RWP)

RWP is a key indicator of water use efficiency, especially under rainfed conditions where no supplementary irrigation is applied. RWP is defined as the crop yield obtained per unit of rainfall received during the cropping season. It reflects how effectively rainwater is converted into agricultural produce. To compute RWP, the total rainfall (in mm) during the crop growth period and the corresponding yield are used (34, 35). The formula for calculating RWP is given in Eqn. 4.

$$\text{Rainwater Productivity (RWP) (kg/m}^3\text{)} = \frac{\text{Grain yield (kg/ha)}}{\text{Rainfall during the crop period (mm)}} \qquad \text{(Eqn. 4)}$$

### Statistical analysis

To assess the effectiveness of RTCMs implemented in response to dry spells and drought conditions, their impacts on crop yield, RWP and economic returns were evaluated using the analysis of variance (ANOVA) over a five-year period. To further distinguish treatment effects, the Least Significant Difference (LSD) test was applied at a significance level of $p < 0.05$, allowing for pairwise comparison of means. All statistical analyses and graphical representations were conducted using Microsoft Excel.

## Results and Discussion

### Rainfall pattern

Seasonal and annual rainfall distribution for 2019–2023 is presented in Table 4. The rainfall analysis from 2019 to 2023, when compared with the long-term average (1974–2023), reveals notable inter-annual variability, especially during the Northeast Monsoon (NEM) season. The NEM rainfall showed positive deviations in four out of the five years, with the highest in 2023 (693.9 mm; +78.47 %) and 2021 (532.3 mm; +36.91 %), indicating wetter than normal monsoon conditions. In contrast, the year 2022 recorded a below-average NEM rainfall (318.1 mm; -18.18 %). Month-wise, November generally received above-average rainfall, particularly in 2021 and 2023, with deviations of +135.99 % and +77.56 % respectively. December 2023 was exceptionally wet (263.9 mm), showing a deviation of +334.05 %. Annual rainfall followed a similar trend with 2023 receiving the highest total (1175.6 mm; +63.23 %) followed closely by the year 2021 (914.7 mm; +27.01 %). Conversely, 2019 was drier than average with a negative deviation of -7.23 %. These variations highlight the

**Table 3**. Real-time contingency measures for various climate aberrations

| Sl. No. | Climatic aberration | Real-time contingency measures |
|---|---|---|
| 1. | Delayed onset of monsoon | • Beyond the optimal sowing window, the selection of alternate crops depends on the farming situation, soil type, rainfall pattern, existing cropping systems and the extent of monsoon delay |
| 2. | Early season drought | • Use of drought-tolerant varieties<br>• Adoption of ridge and furrow system across the slope to enhance *in-situ* moisture conservation<br>• Resowing within 7 to 10 days following subsequent rains, especially when initial germination is below 30 %, to ensure better plant establishment<br>• Thinning of seedlings in small-seeded crops to maintain optimal plant population<br>• Interculture to break soil crust, control weeds and create a soil mulch layer that helps conserve soil moisture<br>• Foliar application of 1 % potassium chloride (KCl) at 45 DAS to reduce transpiration losses |
| 3. | Mid-season drought | • Providing protective or supplemental irrigation, if available<br>• Repeated interculture to remove weeds and create soil mulch to conserve soil moisture<br>• Foliar spray: 1 % KCl foliar spray at 45 DAS to reduce transpiration losses and 0.5 % $ZnSO_4$ during the flowering stage to enhance stress tolerance. |
| 4. | Terminal drought | • Providing life-saving or supplemental irrigation, if available<br>• Harvesting crop at physiological maturity with some realizable yield or harvest for fodder |

**Table 4.** Seasonal and annual distribution of rainfall from 2019–2023

| Month/ Season | Long term Mean RF (RD) (1974–2023) | 2019 | | 2020 | | 2021 | | 2022 | | 2023 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | RF (RD) | DFM (%) | RF (RD) | DFM (%) | RF (RD) | DFM (%) | RF (RD) | DFM (%) | RF (RD) | DFM (%) |
| Oct | 173.8 (9) | 209.2 (13) | 20.37 | 108 (5) | -37.86 | 116.4 (8) | -33.03 | 98 (7) | -43.61 | 156.2 (7) | -10.13 |
| Nov | 154.2 (8) | 141.8 (10) | -8.04 | 213.1 (11) | 38.20 | 363.9 (16) | 135.99 | 189.2 (7) | 22.70 | 273.8 (13) | 77.56 |
| Dec | 60.8 (4) | 75.4 (5) | 24.01 | 152.2 (10) | 150.33 | 52 (5) | -14.47 | 30.9 (3) | -49.18 | 263.9 (5) | 334.05 |
| NEM | 388.8 (21) | 426.4 (28) | 9.67 | 473.3 (26) | 21.73 | 532.3 (29) | 36.91 | 318.1 (17) | -18.18 | 693.9 (25) | 78.47 |
| Annual | 720.2 (41) | 668.1 (46) | -7.23 | 905.6 (47) | 25.74 | 914.7 (60) | 27.01 | 727.9 (45) | 1.07 | 1175.6 (45) | 63.23 |

RF (RD): Rainfall in mm (Rainy days); DFM: Deviations from long term mean.

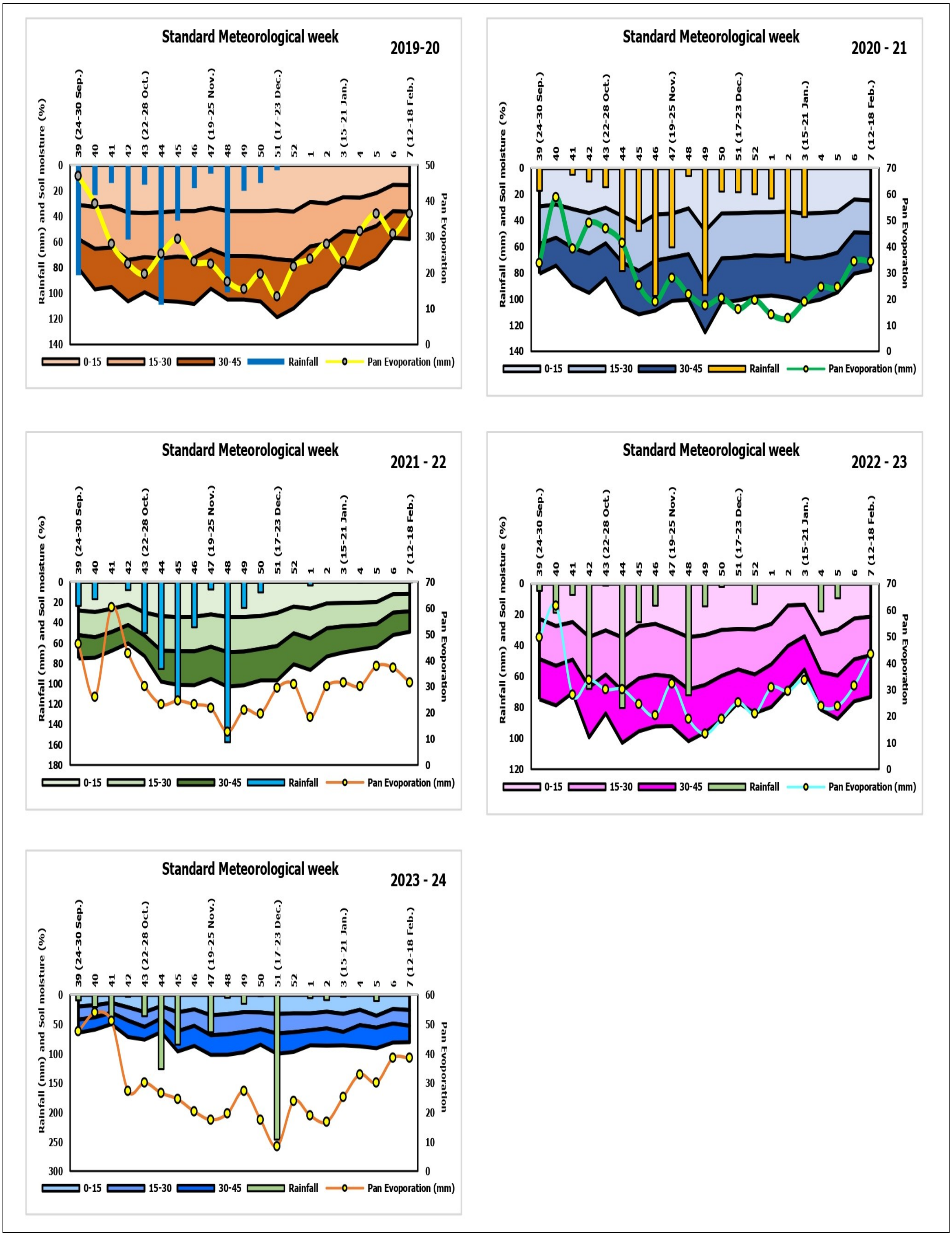

**Fig. 1.** Weekly distribution of rainfall, pan evaporation and soil moisture content (%) at 0–15, 15–30 and 30–45 cm for the study period.

increasing inconsistency in seasonal and annual rainfall patterns, underlining the importance of adaptive water resource planning under rainfed farming conditions.

## Soil water content

The weekly distribution of SWC (0–15 cm, 15–30 cm and 30–45 cm depths), rainfall and pan evaporation across the five cropping years (2019–2024) presented in Fig. 1 highlights the dynamic interaction between rainfall events and atmospheric demand under semi-arid vertisol conditions. Throughout the study period, soil moisture levels in all three layers largely remained within the critical range between FC (35 %) and PWP (14 %), reflecting fluctuations based on rainfall occurrence and evaporative losses. Following rainfall events, the surface layer (0–15 cm) showed a rapid increase in moisture, with subsequent percolation enhancing moisture in deeper layers. In contrast, during dry spells, particularly between standard meteorological week (SMW) 45 to 51 and around SMW 3, soil moisture in the topsoil declined sharply due to increased pan evaporation, while the subsoil (15–45 cm) retained relatively more moisture, acting as a buffer.

This vertical moisture distribution is characteristic of vertisols, where the top layer absorbs and retains water quickly after rainfall but also loses it rapidly during dry periods due to intense evaporation. Meanwhile, the deeper layers maintain better moisture stability, which becomes critical for sustaining crop growth during rainless periods. Importantly, despite rainfall deficits and dry spells during certain weeks, sufficient soil moisture was preserved during the crop's reproductive and maturity stages. This was largely due to effective soil moisture conservation practices such as timely crack sealing, *in-situ* mulching and the maintenance of surface cover, which minimized evaporative losses and enhanced subsoil moisture retention. These adaptive measures helped the crop to withstand terminal drought conditions and ensured successful completion of physiological maturity, reinforcing the importance of real-time moisture management in vertisol-based dryland agriculture.

## Dryness and wetness analysis based on rainfall to pan evaporation ratio

An analysis of the rainfall to pan evaporation ratio (R/E) from SMW 39 to 07 over five cropping seasons (2019–20 to 2023–24) presented in Table 5 revealed significant inter-annual and intra-seasonal variability in moisture availability. The classification used was R/E < 0.5 as dry, 0.5–1.5 as normal and > 1.5 as wet. The onset of the crop season typically begins around SMW 40, making the early SMWs (39 to 44) crucial for crop establishment. In 2019–20, the season commenced favorably with predominantly wet or normal conditions up to SMW 45. However, from SMW 47 onwards, conditions rapidly shifted to dryness, particularly during the terminal phase (SMW 51 to 07), which affected grain filling. The year 2020–21 experienced a prolonged dry spell during the early crop stages( SMW 40 to 43), coinciding with poor germination that necessitated resowing, although mid-season conditions (SMW 44 to 49) were largely wet and supported recovery. The late season had mixed conditions but remained relatively better compared to other years. In 2021–22, early crop stages were affected by consecutive dry weeks (SMW 40 to 42) with a brief wet spell in SMW 43, enabling partial recovery. However, terminal SMWs (51 to 07) remained entirely dry, contributing to yield stress during grain filling. The 2022–23 season exhibited the most erratic pattern, starting with early dryness (SMW 39 to 41), a brief wet spell in SMW 42 and 44 and a return to mid-season dryness (SMW 46, 50) and complete terminal drought from SMW 51 to 07, except for SMW 52. This aligns with the lowest seasonal rainfall recorded in this year and correspondingly, the lowest sorghum yield under $T_1$. In contrast, 2023–24 had a wet beginning at SMW 44 and 45, followed by mild mid-season dryness (SMW 46 and 50) and terminal dryness from SMW 52 to 07, except for a highly wet SMW 51 (R/E = 29.64) due to a heavy downpour of 246 mm. Despite initial crop establishment being strong due to preseason rains, this excessive moisture followed by terminal drought led to physiological stress during the reproductive phase.

Overall, the analysis highlights that dryness during early SMWs (especially 40 to 43) consistently impacted initial crop establishment, necessitating resowing in three out of five years. Similarly, terminal dryness from SMW 51 to 07 was a common stress across all years, stressing the importance of moisture conservation to support grain filling. The R/E analysis thus proves to be an effective indicator for monitoring seasonal dryness and guiding the timely implementation of RTCM. In rainfed farming systems, such real-time assessments are critical for minimizing crop losses and ensuring sustainable yields under increasing

**Table 5.** Dryness and wetness analysis from SMW 39 to 07 over five cropping seasons (2019–20 to 2023–24)

| SMW | 2019–20 | | 2020–21 | | 2021–22 | | 2022–23 | | 2023–24 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | R/E | Class | R/E | Class | R/E | Class | R/E | Class | R/E | Class |
| 39 (24–30 Sep) | 1.84 | Wet | 0.56 | Normal | 0.51 | Normal | 0.08 | Dry | 0.21 | Dry |
| 40 (01–07 Oct) | 0.59 | Normal | 0.00 | Dry | 0.74 | Normal | 0.31 | Dry | 0.38 | Dry |
| 41 (07–14 Oct) | 0.50 | Normal | 0.13 | Dry | 0.01 | Dry | 0.24 | Dry | 1.09 | Normal |
| 42 (15–21 Oct) | 2.62 | Wet | 0.21 | Dry | 0.19 | Dry | 2.08 | Wet | 0.12 | Dry |
| 43 (22–28 Oct) | 0.79 | Normal | 0.31 | Dry | 1.66 | Wet | 0.04 | Dry | 1.20 | Normal |
| 44 (29 Oct–04 Nov) | 4.36 | Wet | 1.92 | Wet | 3.76 | Wet | 2.37 | Wet | 4.71 | Wet |
| 45 (05–11 Nov) | 1.49 | Normal | 1.88 | Wet | 4.68 | Wet | 0.94 | Normal | 3.46 | Wet |
| 46 (12–18 Nov) | 0.79 | Normal | 5.23 | Wet | 1.95 | Wet | 0.72 | Normal | 0.02 | Dry |
| 47 (19–25 Nov) | 0.30 | Dry | 2.18 | Wet | 0.78 | Normal | 0.00 | Dry | 4.14 | Wet |
| 48 (26 Nov–02 Dec) | 5.78 | Wet | 0.28 | Dry | 12.70 | Wet | 4.40 | Wet | 0.24 | Dry |
| 49 (03–09 Dec) | 1.32 | Normal | 5.51 | Wet | 1.23 | Normal | 1.16 | Normal | 0.55 | Normal |
| 50 10–16 Dec) | 0.72 | Normal | 0.90 | Normal | 0.53 | Normal | 0.10 | Dry | 0.12 | Dry |
| 51 (17–23 Dec) | 0.31 | Dry | 1.09 | Normal | 0.00 | Dry | 0.00 | Dry | 29.64 | Wet |
| 52 (24–31 Dec) | 0.00 | Dry | 0.90 | Normal | 0.00 | Dry | 0.67 | Normal | 0.04 | Dry |
| 01 (01–07 Jan) | 0.00 | Dry | 1.70 | Wet | 0.19 | Dry | 0.00 | Dry | 0.29 | Dry |
| 02 (08–14 Jan) | 0.00 | Dry | 5.59 | Wet | 0.00 | Dry | 0.00 | Dry | 0.54 | Normal |
| 03 (15–21 Jan) | 0.02 | Dry | 1.48 | Normal | 0.00 | Dry | 0.00 | Dry | 0.13 | Dry |
| 04 (22–28 Jan) | 0.00 | Dry | 0.00 | Dry | 0.03 | Dry | 0.74 | Normal | 0.00 | Dry |
| 05 (29 Jan–04 Feb) | 0.00 | Dry | 0.00 | Dry | 0.00 | Dry | 0.40 | Dry | 0.37 | Dry |
| 06 (05–11 Feb) | 0.00 | Dry | 0.00 | Dry | 0.00 | Dry | 0.00 | Dry | 0.00 | Dry |
| 07 (12–18 Feb) | 0.00 | Dry | 0.00 | Dry | 0.01 | Dry | 0.00 | Dry | 0.00 | Dry |

**Table 6.** Agricultural drought categories based on PASM values for study period from 2019–20 to 2023–24

| SMW | 2019–20 | | 2020–21 | | 2021–22 | | 2022–23 | | 2023–24 | |
|---|---|---|---|---|---|---|---|---|---|---|
| | PASM | ADC | PASM | ADC | PASM | ADC | PASM | ADC | PASM | ADC |
| 39 (24–30 Sep) | 61.31 | MID | 61.61 | MID | 52.95 | MID | 52.23 | MID | 35.57 | MOD |
| 40 (01–07 Oct) | 87.48 | NOD | 51.77 | MID | 51.92 | MID | 58.45 | MID | 27.52 | MOD |
| 41 (07–14 Oct) | 84.44 | NOD | 75.30 | NOD | 41.25 | MOD | 45.57 | MOD | 12.63 | SVD |
| 42 (15–21 Oct) | 92.39 | NOD | 84.74 | NOD | 29.55 | MOD | 91.14 | NOD | 47.33 | MOD |
| 43 (22–28 Oct) | 87.78 | NOD | 67.06 | MID | 49.54 | MOD | 66.58 | MID | 54.38 | MID |
| 44 (29 Oct–04 Nov) | 68.29 | MID | 96.50 | NOD | 89.24 | NOD | 96.80 | NOD | 34.04 | MOD |
| 45 (05–11 Nov) | 96.34 | NOD | 96.14 | NOD | 94.17 | NOD | 84.95 | NOD | 86.23 | NOD |
| 46 (12–18 Nov) | 87.64 | NOD | 104.88 | NOD | 94.65 | NOD | 79.90 | NOD | 71.28 | MID |
| 47 (19–25 Nov) | 86.60 | NOD | 94.52 | NOD | 84.78 | NOD | 79.54 | NOD | 95.38 | NOD |
| 48 (26 Nov–02 Dec) | 93.34 | NOD | 93.03 | NOD | 97.02 | NOD | 95.08 | NOD | 95.06 | NOD |
| 49 (03–09 Dec) | 98.71 | NOD | 110.34 | NOD | 94.68 | NOD | 86.09 | NOD | 88.40 | NOD |
| 50 10–16 Dec) | 99.76 | NOD | 96.39 | NOD | 87.23 | NOD | 73.21 | MID | 68.05 | MID |
| 51 (17–23 Dec) | 91.60 | NOD | 93.79 | NOD | 87.23 | NOD | 55.68 | MID | 92.54 | NOD |
| 52 (24–31 Dec) | 90.55 | NOD | 89.48 | NOD | 62.12 | MID | 66.33 | MID | 87.28 | NOD |
| 01 (01–07 Jan) | 89.44 | NOD | 87.83 | NOD | 70.96 | MID | 60.05 | MID | 69.75 | MID |
| 02 (08–14 Jan) | 79.65 | NOD | 90.66 | NOD | 49.91 | MOD | 41.92 | MOD | 70.57 | MID |
| 03 (15–21 Jan) | 62.82 | MID | 96.83 | NOD | 43.66 | MOD | 21.71 | SVD | 69.83 | MID |
| 04 (22–28 Jan) | 62.03 | MID | 92.58 | NOD | 39.28 | MOD | 62.94 | MID | 72.37 | MID |
| 05 (29 Jan–04 Feb) | 50.02 | MID | 84.06 | NOD | 35.37 | MOD | 72.23 | MID | 77.39 | NOD |
| 06 (05–11 Feb) | 23.69 | SVD | 61.44 | MID | 16.62 | SVD | 54.26 | MID | 62.31 | MID |
| 07 (12–18 Feb) | 25.29 | MOD | 57.07 | MID | 11.64 | SVD | 49.77 | MOD | 61.12 | MID |

climate variability.

## Observation of agricultural drought conditions

The weekly progression of agricultural drought conditions from 2019–20 to 2023–24 as assessed using PASM values presented in Table 6 highlights significant interannual variability in drought severity during the rabi season (SMW 39 to 07). In 2019–20, the season commenced with moderate to mild drought (SMW 39–40) followed by consistently normal conditions (NOD) from mid-October to February, except for isolated weeks showing mild or severe drought. The 2020–21 season also remained predominantly under normal conditions, except for early October (SMW 40) and mid-February (SMW 06–07), which recorded mild to moderate drought. In contrast, 2021–22 showed widespread moderate drought from early October through late January, with severe drought episodes in early and mid-February. The 2022–23 season was marked by a fluctuating trend, beginning with mild drought, shifting to normalcy during mid-October to early December, but again reverting to mild and moderate drought through January and February, including a severe drought in SMW 03. Notably, 2023–24 experienced more drought stress early in the season, with moderate to severe drought recorded in SMW 39 to 42. Though conditions gradually improved, moderate to mild drought persisted through much of the season, with a return to normal in some weeks from mid-November (46th SMW) onwards. Overall, the data indicate a shift towards increased early-season drought intensity and variability in recent years, which could impact crop establishment and productivity.

## Impact of RTCM on sorghum under rainfed conditions

In rainfed regions, particularly under semi-arid vertisols, cropping systems are highly vulnerable to intra-seasonal rainfall variability and prolonged dry spells (21). To address this, RTCM was implemented during five consecutive sorghum-growing seasons from 2019–20 to 2023–24. The primary variety used was Sorghum K12, a photo-insensitive, short-duration (95–100 days), drought-tolerant variety, resistant to downy mildew and moderately resistant to shoot fly and stem borer. It is suitable for both summer

**Table 7.** Implementation details of real-time contingency measures (RTCM) for sorghum during 2019–2024

| Year | OM | DOS | DORS | DOH | RF, mm | SMW | Crop stage | Dryness | ADC | RTCM |
|---|---|---|---|---|---|---|---|---|---|---|
| 2019–20 | 16-10-19 | 02-10-19 | - | 17-01-20 | 513.10 | 51-03 | Maturity, Ripening | Terminal | NOD to MID | Drought, MCP, Crack closure, Mulching |
| 2020–21 | 28-10-20 | 03-10-20 | 25-10-20 | 13-02-21 | 591.80 | 40-43 | Seeding | Early Season | MID to NOD | Resowing |
| 2021–22 | 25-10-21 | 01-10-21 | 24-10-21 | 14-02-22 | 550.80 | 41-42 | Seeding | Early Season | MOD | Resowing |
| | | | | | | 51-07 | Maturity Ripening | Terminal | MOD to SVD | Drought, MCP, Crack closure, Mulching |
| 2022–23 | 29-10-22 | 01-10-22 | 21-10-22 | 10-02-23 | 348.90 | 40-41 | Seeding | Early | MID to MOD | Resowing |
| | | | | | | 49-50 | Vegetative | Mid-season | NOD-MID | Foliar spray |
| | | | | | | 01-06 | Maturity, Ripening | Terminal | MID, MOD, SVD | Drought, MCP, Crack closure, Mulching |
| 2023–24 | 21-10-23 | 01-10-23 | - | 23-01-24 | 535.50 | 46 | Vegetative | Mid-season | MID | Foliar spray |
| | | | | | | 52-03 | Maturity, Ripening | Terminal | MID | Drought, MCP, Crack closure, Mulching |

OM: Onset of monsoon; DOS: date of sowing; DORS: date of resowing; DOH: date of harvest; RF: rainfall, mm; SMW: standard meteorological week; ADC: Agricultural drought category, NOD: No drought; MID: Mild drought; MOD: Moderate drought; SVD: Severe drought.

and winter seasons and has a rainfed potential yield of 3123 kg/ha. Implementation details of RTCM for sorghum during 2019–20 to 2023–24 are presented in Table 7.

Typically, the Northeast Monsoon in the study area commences between the 42nd and 44th SMW. During the study period from 2019–20 to 2023–24, the Northeast Monsoon commenced on time across all years, with no significant delays in its onset. Consequently, the implementation of RTCM specifically aimed at managing delayed monsoon onset was not required. However, rainfall occurred as early as the 39th SMW in several years, prompting initial sowing across all five years during the 40th SMW, in line with pre-monsoon season sowing guidelines. Despite this, resowing was necessitated in 2020–21, 2021–22 and 2022–23 due to poor germination attributed to early-season dryness, as indicated by low PASM values and (R/E) ratios. Dryness events were categorized based on crop growth stages: early season (1–15 DAS, seedling stage), mid-season (16–40 DAS, vegetative/grand growth) and terminal stage (41–105 DAS, flowering to ripening). Drought severity was assessed using PASM thresholds: no drought (NOD: 76 %–100 %), mild drought (MID: 51 %–75 %), moderate drought (MOD: 26 %–50 %) and severe drought (SVD: < 25 %).

Accordingly, contingency measures were selected and implemented based on both the stage and intensity of dryness. Resowing was carried out when early-season drought impaired crop emergence and stand. During the mid-season drought, 1 % potassium chloride (KCl) foliar spray was applied at 45 DAS to reduce transpiration losses and 0.5 % zinc sulfate ($ZnSO_4$) was sprayed during the flowering stage to enhance stress tolerance. Moisture conservation was a key strategy across all years: ridge and furrow formation at 45 cm spacing, closure of deep soil cracks by hoeing and spreading of crop residue as mulch helped improve *in-situ* moisture retention and reduce evaporative losses. All years, except 2022–23, recorded seasonal rainfall > 500 mm, which was approximately 30 % higher than the long-term average. In contrast, 2022–23 received only 348.9 mm, compounding the effects of multiple dry spells.

## Crop response to real-time contingency measures

Table 8 presents the combined analysis of yield productivity, water productivity and economics of sorghum for 2019–20 to 2023–24. The implementation of RTCM significantly influenced crop performance. The mean grain yield of sorghum under $T_1$ (treatment with RTCM) was 2984 kg/ha, which was only 4.5 % lower than the potential yield of K12. In contrast, the control treatment $T_2$ (without RTCM), where only resowing and recommended nutrient management were practiced, recorded an average yield of 2050 kg/ha, indicating a 34.4 % yield reduction under non-adaptive management. These yield differences were statistically significant, with the LSD at 5 % for yield being 268.5 kg/ha and the mean difference ($T_1$–$T_2$) of 934 kg/ha far exceeding this threshold. Similar significant gains were observed in RWP and benefit-cost (B:C) ratio, where T1 recorded 0.59 $kg/m^3$ and 2.66 respectively, compared to 0.40 $kg/m^3$ and 1.83 under $T_2$.

In 2019–20, the crop experienced terminal dryness during the maturity and ripening stages (51st SMW of 2019 to 03rd SMW of 2020), yet PASM values indicated no to mild drought conditions. The timely adoption of moisture conservation practices, such as ridge-furrow planting, mulching and crack closure, enabled the crop to retain soil moisture during the grain-filling phase. Consequently, $T_1$ recorded 3351 kg/ha, a significant improvement over $T_2$ (2124 kg/ha), with an RWP of 0.65 and B:C of 2.99, reflecting high physiological water productivity and economic efficiency.

In 2020–21, early season dryness (SMW 40 to 43) disrupted the seedling stage despite rainfall occurrence. PASM values showed mild to no drought, suggesting moisture was insufficient for sustained germination, necessitating resowing on the 43rd SMW. The well-established resown crop, combined with favorable rainfall distribution, resulted in the highest yield (3424 kg/ha) under $T_1$, significantly higher than $T_2$ (2353 kg/ha). RWP was 0.58 and B:C reached 3.06, the highest across all years. These results highlight the importance of monitoring early germination, as initial stand failure without corrective measures severely reduces yield.

The 2021–22 season also required resowing due to early season dryness (SMW 41 to 42), with PASM indicating moderate drought. Later, terminal dryness from SMW 51 to 07 during the maturity phase coincided with moderate to severe drought conditions. The stress combination impacted yield, but the $T_1$ plot still recorded 2981 kg/ha, outperforming $T_2$ by 860 kg/ha, owing to early resowing, moisture conservation and mid-season stress tolerance measures. The corresponding RWP (0.54) and B:C (2.66) indicated efficient moisture utilization despite adverse conditions.

The 2022–23 season was the most challenging, with multiple stress phases: early-season dryness (SMW 40 to 41), mid-season stress during the vegetative stage (SMW 49 to 50) and terminal stress (SMW 01 to 06). Rainfall was only 348.9 mm, far below the mean rainfall. Despite foliar sprays and full deployment of moisture-saving practices, crop growth was stunted and grain filling was suboptimal. Despite multiple stress events, $T_1$ plots still achieved 2265 kg/ha, substantially more than $T_2$ (1425 kg/ha). This 58.9 % yield improvement under $T_1$, under extreme conditions, underscores the resilience imparted by the RTCM approach. RWP was 0.64 ($T_1$) vs. 0.40 ($T_2$) and B:C was 2.02 ($T_1$) vs. 1.27 ($T_2$), reaffirming the cost-effectiveness of stress mitigation practices even in poor rainfall years.

In 2023–24, sowing was timely and good rainfall distribution (SMW 40 to 45) led to excellent crop establishment. A

**Table 8.** Combined analysis of yield productivity, water productivity and economics of sorghum for 2019–20 to 2023–24

| Year | Grain yield (kg/ha) | | | Biomass yield (kg/ha) | | Harvest Index (%) | | RWP ($kg/m^3$) | | B-C ratio | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $T_1$ | $T_2$ | Yield increase (%) | $T_1$ | $T_2$ | $T_1$ | $T_2$ | $T_1$ | $T_2$ | $T_1$ | $T_2$ |
| 2019-20 | 3351 | 2124 | 57.8 | 11398 | 8107 | 29.4 | 26.2 | 0.65 | 0.41 | 2.99 | 1.9 |
| 2020-21 | 3424 | 2353 | 45.5 | 10974 | 9604 | 31.2 | 24.5 | 0.58 | 0.40 | 3.06 | 2.1 |
| 2021-22 | 2981 | 2121 | 40.5 | 11378 | 10005 | 26.2 | 21.2 | 0.54 | 0.39 | 2.66 | 1.89 |
| 2022-23 | 2265 | 1425 | 58.9 | 9245 | 6169 | 24.5 | 23.1 | 0.64 | 0.40 | 2.02 | 1.27 |
| 2023-24 | 2898 | 2225 | 30.2 | 10424 | 10545 | 27.8 | 21.1 | 0.54 | 0.42 | 2.59 | 1.99 |
| Mean | 2984 | 2050 | 45.6 | 10684 | 8886 | 27.8 | 23.2 | 0.59 | 0.40 | 2.66 | 1.83 |
| Mean difference | 934 | | | 1798 | | 4.6 | | 0.19 | | 0.83 | |
| LSD (5 %) | 268.5 | | | 1746 | | 2.86 | | 0.07 | | 0.24 | |

mid-season dryness (SMW 46) occurred during the vegetative stage, with PASM indicating mild drought, managed by foliar spraying. Subsequently, a terminal dryness episode from SMW 52 to 03 affected maturity and ripening. Though stress was mild, its impact was compounded by a heavy rainfall event (246 mm) in SMW 51, which created temporary waterlogging despite drainage efforts. $T_1$ yielded 2898 kg/ha, compared to the yield of 2225 kg/ha in $T_2$. The RWP was 0.54 and B:C was 2.59 under $T_1$, indicating that even in well-distributed rainfall years, RTCM offers a buffer against unseasonal rainfall events and late-season stress.

For biomass yield, the average under $T_1$ was 10684 kg/ha, significantly higher than $T_2$ with 8886 kg/ha. The mean difference ($T_1$-$T_2$) was statistically significant and the LSD (5 %) was 1,746 kg/ha. In three out of five years (2019–20, 2021–22 and 2022–23), the observed differences exceeded the LSD, confirming a significant positive impact of RTC measures. For the harvest index, $T_1$ recorded a mean of 27.8 %, while $T_2$ had 23.2 %, showing a consistent increase in partitioning of biomass to grain under RTCM interventions, with LSD (5 %) of 2.86 %. This confirms that the improvements in harvest index due to RTCM were statistically significant in all years. Overall, the five-year dataset clearly shows that RTC measures significantly enhanced yield, water use efficiency and economic returns. Yield improvement was consistent and statistically significant across all years, with the mean differences exceeding LSD values for all parameters.

Between 2011 and 2014, RTCMs were implemented across 34 selected villages to address weather aberrations and enhance field-level agricultural productivity. These efforts were carried out through 23 network centres of the AICRPDA, under the Technology Demonstration component of the NICRA project (19, 31, 32). The intervention had a significant impact, particularly in managing early-season, mid-season and terminal droughts (33). Timely identification of crop stress stages, combined with stage-specific interventions, enabled crops to complete their lifecycle more effectively than in control plots, which lacked such support. These results underscore the critical importance of real-time, adaptive management in stabilizing rainfed sorghum yields under increasingly variable climatic conditions.

## Conclusion

This five-year field study conclusively demonstrates that the implementation of RTCM plays a pivotal role in stabilizing sorghum productivity under rainfed conditions, especially in the vertisols of semi-arid regions of southern Tamil Nadu. Rainfed farming in these regions is highly susceptible to the vagaries of monsoon rainfall, often leading to poor crop establishment, mid-season stress and terminal moisture deficits. The adoption of stage-specific and weather-responsive measures such as timely resowing, moisture conservation and foliar nutrient sprays effectively minimized yield losses and improved crop resilience across varying rainfall years. On average, RTCM resulted in a 34.4 % higher yield, 47.5 % greater rainwater productivity and significantly improved ($p < 0.05$) economic returns, as evidenced by higher benefit-cost ratios across all five years. For resource-poor farmers in these fragile agro-ecosystems, RTCM not only enables farmers to cope with weather uncertainties but also serves as a low-cost and scalable approach to safeguard their livelihoods. By aligning crop management with real-time weather conditions and soil moisture status, farmers can mitigate drought impacts, ensure better plant growth and recover yield potential that would otherwise be lost. Therefore, it is recommended that RTCM strategies be mainstreamed through local extension systems, supported by real-time weather advisories and decision-support tools. Emphasis should also be placed on promoting drought-tolerant crop varieties, enhancing on-farm rainwater management and building community-level awareness to adopt these adaptive measures. Ensuring timely implementation of RTCM is thus crucial for improving the profitability, sustainability and climate resilience of rainfed agriculture in southern Tamil Nadu.

## Acknowledgements

The authors are very much thankful to the Project Coordinating Unit of the All India Coordinated Research Project for Dryland Agriculture, ICAR–Central Research Institute for Dryland Agriculture, Hyderabad and the Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu for extending technical guidance and financial support.

## Authors' contributions

BBS, JVNSP conceptualized the study and contributed essential suggestions. BBS, VS, MJ conducted field work and collected data. BBS, MM and KAG carried out the field data analysis. All authors performed the experiments, authored and reviewed the draft of the article and approved the final draft.

## Compliance with ethical standards

**Conflict of interest:** Authors do not have any conflict of interest to declare.

**Ethical issues:** None

**Declaration of generative AI and AI-assisted technologies in the writing process:** During the preparation of this work, the authors used ChatGPT solely to improve language and readability. After using the tool, the authors carefully reviewed and edited the content and take full responsibility for the final publication.

## References

1. NRAA. Prioritization of districts for development planning in India: A composite index approach. New Delhi: National Rainfed Area Authority; 2020. p. 85.
2. Sharma KD. Rain-fed agriculture could meet the challenges of food security in India. Curr Sci. 2011;100(11):1615–16.
3. Rao CS, Rejani R, Rama Rao CA, Rao KV, Osman M, Reddy KS, et al. Farm ponds for climate-resilient rainfed agriculture. Curr Sci. 2017;112(3):471–77. https://doi.org/10.18520/cs/v112/i03/471-477
4. Montieth JL. Weather and water in the Sudano-Sahelian zone. In: Sivakumar MVK, Wallace JS, Rénard C, Giroux C, editors. Soil Water Balance in the Sudano-Sahelian Zone: Proceedings of the International Workshop; 1991 Feb; Niamey, Niger. Wallingford (UK): IAHS Press, Institute of Hydrology; 1991. p. 11–30.
5. Bal SK, Minhas PS. Atmospheric stressors: challenges and coping strategies. In: Minhas PS, editor. Abiotic stress management for resilient agriculture. Singapore: Springer Nature; 2017. p. 9–50. https://doi.org/10.1007/978-981-10-5744-1_2

6. Mishra AK, Singh VP. A review of drought concepts. J Hydrol. 2010;391:202–16. https://doi.org/10.1016/j.jhydrol.2010.07.012

7. Wilhite DA, Glantz MH. Understanding the drought phenomenon: the role of definitions. Water Int. 1985;10:111–20. https://doi.org/10.1080/02508068508686328

8. Tebaldi C, Hayhoe K, Arblaster JM, Meehl GA. Going to the extremes: an inter-comparison of model-simulated historical and future changes in extreme events. Clim Change. 2006;79:185–211. https://doi.org/10.1007/s10584-006-9051-4

9. Bal SK, Sandeep VM, Vijaya Kumar P, Subbarao AVM, Pramod VP, Srinivasarao Ch, et al. Assessing impact of dry spells on the principal rainfed crops in major dryland regions of India. Agric For Meteorol. 2022;313:108768. https://doi.org/10.1016/j.agrformet.2021.108768

10. Douville H, Chauvin F, Broqua H. Influence of soil moisture on the Asian and African monsoons. Part I: Mean monsoon and daily precipitation. J Clim. 2001;14(11):2381–403. https://doi.org/10.1175/1520-0442(2001)014<2381:IOSMOT>2.0.CO;2

11. Namias J. Factors in the initiation, perpetuation and termination of drought. Extr Publ IASH Comm Surf Waters. 1960;51:81–94.

12. Machado S, Bynum ED, Archer TL, Bordovsky J, Rosenow DT, Peterson C, et al. Spatial and temporal variability of sorghum grain yield: influence of soil, water, pests and diseases relationships. Precis Agric. 2002;3:389–406. https://doi.org/10.1023/A:1021597023005

13. Stephens DJ, Lyons TJ. Rainfall-yield relationships across the Australian wheat belt. Aust J Agric Res. 1998;49:211–24. https://doi.org/10.1071/A96139

14. Bal SK, Shivaramu HS, Vijaya Kumar P, Lingaraj H, Sandeep VM, SubbaRao AVM, et al. Re-evaluating soil moisture based drought criteria for rainfed crops in peninsular India. Front Environ Sci. 2024;12:1319912. https://doi.org/10.3389/fenvs.2024.1319912

15. Anonymous. Manual for drought management. New Delhi: Department of Agriculture, Cooperation & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India; 2016. p. 37–9.

16. Doorenbos J, Pruitt WO. Guidelines for predicting crop water requirements. FAO Irrig Drain Pap. 1977;24:193.

17. ICAR-CRIDA. Manual on drought management: real time contingency planning. Hyderabad: Central Research Institute for Dryland Agriculture; 2020.

18. Chary RG, Venkateswarlu B, Sharma SK, Mishra SK, Rana DS, Kute G. Agronomic research in dry land farming in India: an overview. Indian J Agron. 2012;57:157–67.

19. Srinivasarao Ch, Ravindra Chary G, Mishra PK, Nagarjuna Kumar R, Maruthisankar GR, Venkateswarlu B, et al. Real time contingency planning: initial experiences from AICRPDA. Hyderabad: ICAR-CRIDA; 2013. p. 63.

20. Reddy GS, Ramakrishna YS, Ravindra Chary G, Maruthisankar GR. Crop and contingency planning for rainfed regions of India: a compendium by AICRPDA. Hyderabad: ICAR-CRIDA; 2008. p. 174.

21. AICRPDA. All India Coordinated Research Project for Dryland Agriculture Reports. Kovilpatti: ICAR–Agricultural Research Station, Tamil Nadu Agricultural University; 2021.

22. Soil Survey Staff. Soil taxonomy: A basic system of soil classification for making and interpreting soil surveys. 2nd ed. Agriculture Handbook No. 436. Washington, DC: USDA, NRCS; 1999.

23. Crop Production Guide. Chennai: Department of Agriculture, Government of Tamil Nadu; 2020.

24. Liao Y, Cao HX, Xue WK, Liu X. Effects of the combination of mulching and deficit irrigation on the soil water and heat, growth and productivity of apples. Agric Water Manag. 2021;243:106482. https://doi.org/10.1016/j.agwat.2020.106482

25. Mo F, Wang JY, Xiong YC, Nguluu SN, Li FM. Ridge-furrow mulching system in semiarid Kenya: a promising solution to improve soil water availability and maize productivity. Eur J Agron. 2016;80:124–36. https://doi.org/10.1016/j.eja.2016.07.005

26. Gardner WH. Water content. In: Klute A, editor. Methods of soil analysis. Part 1. 2nd ed. Madison: ASA and SSSA; 1986. p. 493–544. https://doi.org/10.2136/sssabookser5.1.2ed.c21

27. Rossato L, Alvalá RC, Marengo JA, Zeri M, Cunha AP, Pires L, Barbosa HA. Impact of soil moisture on crop yields over Brazilian semiarid. Front Environ Sci. 2017;5:73. https://doi.org/10.3389/fenvs.2017.00073

28. Sushama L, Khaliq MN, Laprise R. Dry spell characteristics over Canada in a changing climate as simulated by the Canadian RCM. Glob Planet Change. 2010;74:1–14. https://doi.org/10.1016/j.gloplacha.2010.07.004

29. Vinnarasi R, Dhanya CT. Changing characteristics of extreme wet and dry spells of Indian monsoon rainfall. J Geophys Res Atmos. 2016;121(5):2146–60. https://doi.org/10.1002/2015JD024310

30. Mishra SK, Simranjeet KS, Chandran MAS, Bal SK. Dynamics of dry spells and their impact on crop productivity. Indian J Dryland Agric Res Dev. 2024;39(2):22–32. https://doi.org/10.5958/2231-6701.2024.00013.6

31. Srinivasarao CH, Venkateswarlu B, Sikka AK, Prasad YG, Ravindra Chary G, Rao KV, et al. District agricultural contingency plans to address weather aberrations and for sustainable food security in India. Hyderabad: ICAR-CRIDA; 2015. p. 22.

32. Srinivasarao CH, Chary GR, Rani N, Baviskar VS. Real time implementation of agricultural contingency plans to cope with weather aberrations in Indian agriculture. Mausam. 2016;67(1):183–94. https://doi.org/10.54302/mausam.v67i1.1176

33. AICRPDA. NICRA annual reports 2011–2014. Kovilpatti: ICAR–Agricultural Research Station, Tamil Nadu Agricultural University; 2025.

34. Molden D. Accounting for water use productivity. SWIM Publication No. 1. Colombo: International Water Management Institute; 2001.

35. Sharma BR, Rao KV, Vittal KPR, Ramakrishna YS, Amarasinghe U. Estimating the potential of rainfed agriculture in India: prospects for water productivity improvements. Agric Water Manag. 2010;97:23–30. https://doi.org/10.1016/j.agwat.2009.08.002

## Additional information

**Peer review**: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

**Reprints & permissions information** is available at https://horizonepublishing.com/journals/index.php/PST/open_access_policy

**Publisher's Note**: Horizon e-Publishing Group remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Indexing**: Plant Science Today, published by Horizon e-Publishing Group, is covered by Scopus, Web of Science, BIOSIS Previews, Clarivate Analytics, NAAS, UGC Care, etc
See https://horizonepublishing.com/journals/index.php/PST/indexing_abstracting

**Publisher information:** Plant Science Today is published by HORIZON e-Publishing Group with support from Empirion Publishers Private Limited, Thiruvananthapuram, India.