EQA - International Journal of Environmental Quality
ISSN 2281-4485 - Vol. 72 (2026): 65-73
Journal homepage: https://eqa.unibo.it/

published by

Rainfall distribution patterns during the Southwest Monsoon in Kota District, Rajasthan (2018–2023) and their impact on crop production

Ankit Kumar Meena[1]*, Harphool Meena[2], Fawaz Parapurath[1], Rathika[1], Akshaya Shanmugam[1]

[1] Agro Climate Research Centre, Tamil Nadu Agricultural University, Coimbatore, Tamil Nadu, India.
[2] Agricultural Research Station, Agriculture University, Kota, Rajasthan, India

* Corresponding author E.mail: ankitoffice52@gmail.com

Article info
Received 10/8/2025; received in revised form 27/11/2025; accepted 11/1/2026
DOI: 10.60923/issn.2281-4485/22641

Abstract
This study investigates the rainfall distribution patterns during the southwest monsoon (SWM) in Kota district, Rajasthan, from 2018 to 2023, and their effects on crop production. Kota lies in the humid southeastern plain where agriculture depends primarily on rainfall, making the region vulnerable to droughts and floods due to monsoon variability. Rainfall data were recorded at the Agro-Meteorological Field Unit, ARS Kota, and categorized according to IMD classifications. Results revealed significant inter-annual variability in both total seasonal rainfall and weekly distribution, with notable extremes such as 1322.4 mm in 2019 (+48.92% above normal) and 497.7 mm in 2018 (−43.95% below normal). Onset and withdrawal dates of the monsoon varied widely, influencing sowing times, crop growth, and yield potential. Analysis showed that the amount, intensity, and temporal distribution of rainfall critically affect soil moisture availability, plant physiological processes, and yield outcomes. High-intensity rainfall often led to surface runoff and reduced infiltration, while well-distributed rainfall enhanced crop performance. Adaptation mechanisms in crops included morphological, physiological, and developmental responses to moisture stress, alongside management strategies to optimize resource use. The study emphasizes the importance of effective rainfall, timely sowing, and adaptive cropping patterns to mitigate the adverse impacts of rainfall variability under changing climatic conditions.

Keywords: *Rainfall distribution, Southwest monsoon, Kota district, Crop production, Climate variability, Effective rainfall, Adaptation strategies.*

Introduction

Kota is situated in the humid southeastern plains of Rajasthan, where agriculture forms the primary livelihood for the majority of the population. Most parts of Kota district experience a humid climate, while the remaining areas fall under a transitional humid to sub-arid zone. Rainfall serves as the principal source of water for agricultural activities and plays a crucial role in recharging both surface and groundwater resources. The Southwest Monsoon (SWM) season constitutes the main rainy period in the region. However, the high variability of the monsoon rainfall renders the district vulnerable to natural calamities such as droughts and floods. The geographical location of Kota, combined with its topography and its interaction with prevailing monsoon wind patterns, is a major factor influencing the spatial and temporal variability of rainfall. Based on data collected from 2018 to 2023, the average seasonal rainfall over Kota is approximately 888.0 mm, with the normal onset date of the monsoon around 15th June. The withdrawal of the monsoon typically begins from western Rajasthan

EQA 72 (2026): 65 - 73

DOI: 10.60923/issn.2281-4485/22641

However, the high variability of the monsoon rainfall renders the district vulnerable to natural calamities such as droughts and floods. The geographical loca-tion of Kota, combined with its topography and its interaction with prevailing monsoon wind patterns, is a major factor influencing the spatial and temporal va-riability of rainfall. Based on data collected from 2018 to 2023, the average seasonal rainfall over Kota is approximately 888.0 mm, with the normal onset date of the monsoon around 15th June. The withdrawal of the monsoon typically begins from western Rajasthan around 15th September. The performance of the monsoon over the past six years in Kota is summarized in table 1.

Table 1. *Rainfall during southwest monsoon over Kota in last few years*

Year	Actual rainfall (mm)	Normal rainfall (mm)	Departure from normal (%)
2018	497.7	888.0	-43.95
2019	1322.4	888.0	48.92
2020	617.1	888.0	-30.51
2021	1120	888.0	26.13
2022	1121.5	888.0	26.30
2023	649.4	888.0	-26.87

Experiment and methodology

The experiment titled "Rainfall Distribution during the Southwest Monsoon in Kota District and Its Effect on Crop Production" was systematically conducted at the Agro-Meteorological Field Unit (AMFU), Agricultural Research Station (ARS), Kota, Rajasthan, India, over tsix consecutive monsoon seasons from 2018 to 2023. Kota district is geographically positioned between 25°11'0" N latitude and 75°50'0" E longitude, characterized by a semi-arid climate with highly variable monsoon rainfall patterns. Meteorological data, including daily rainfall, temperature, humidity, wind speed, and solar radiation, were meticulously recorded manually using standard instruments at the Agro-Meteorology Observatory, which operates under the Gramin Krishi Mausam Sewa (GKMS) project. This project aims to provide localized weather information to support agricultural decision-making. Data collection followed strict protocols to ensure accuracy and consistency. The collected meteorological parameters were then correlated with crop phenology and yield data to analyze the impact of rainfall variability on crop production. The detailed experimental design, data collection methods, and analytical procedures employed in this study are described in the following secions. Recording 24-hour rainfall over a station different category according IMD following in table 2..

Table 2. *Rainfall category according IMD*

Categories	Rainfall (mm/day)
Very light rainfall	Trace – 2.4
Light rainfall	2.5-15.5
Moderate rainfall	15.6-64.4
Heavy rainfall	64.5-115.5
Very heavy rainfall	115.6-204.4
Extremally heavy rainfall	More 204.4

Rainfall data collection during southwest monsoon over station Agro-Meteorological Field Units at ARS Kota in last few years following table3.

SMW	YEARS					
	2018	2019	2020	2021	2022	2023
11 June – 17 June	0.0	0.0	28.0	0.0	18.0	0.0
18 June – 24 June	0.0	58.0	50.0	0.0	67.0	30.0
25 June – 01 July	0.0	47.3	13.0	0.0	35.9	132.0
02 Jul- 08 Jul	0.0	165.5	31.0	0.0	56.5	109.5
09 Jul- 15 Jul	39.0	0.0	37.5	75.0	68.0	23.0
16 Jul- 22 Jul	81.0	0.1	29.0	15.0	85.5	90.0
23 Jul- 29 Jul	27.0	246.0	0.0	129.0	241.0	101.5
30 Jul- 05 Aug	0.0	116.0	63.0	604.0	54.6	27.5
06 Aug - 12 Aug	43.0	148.5	11.0	235.0	110.0	0.0
13 Aug - 19 Aug	25.0	331.0	111.0	12.0	64.0	12.7
20 Aug - 26 Aug	117.4	30.0	107.5	6.0	248.0	9.0
27 Aug - 02 Sep	11.4	57.0	43.1	20.0	4.0	0.0
03 Sep- 09 Sep	153.5	32.0	93.0	0.0	0.0	26.3
10 Sep- 16 Sep	0.4	91.0	0.0	24.0	69.0	87.9

Table 3
Weekly weather data recorded at the Agro-Meteorological Field Unit, Agricultural Research Station (ARS), Kota, Agriculture University, Kota, Rajasthan, India, during the Southwest Monsoon seasons from 2018 to 2023.

EQA 72 (2026): 65 - 73

DOI: 10.60923/issn.2281-4485/22641

Results

Actual onset & withdrawal dates of SW monsoon over Rajasthan

The actual onset and withdrawal dates of the Southwest Monsoon over Rajasthan are presented in the following table 4.

Table 4

YEAR	ONSET DATE	WITHDRAWL DATE
2018	26-Jun	1-Oct
2019	2-Jul	11-Oct
2020	24-Jun	6-Oct
2021	18-Jun	not yet declared
2022	30-Jun	not yet declared
2023	25-Jun	30-Sep

Actual onset and withdrawal dates of SW monsoon over Rajasthan 2018. The Southwest Monsoon in 2018 initially reached the South Andaman Sea and Nicobar Islands on 25th May, which was five days later than the normal onset date. However, the subsequent progression of the monsoon was relatively rapid. It set in over Kerala on 29th May, three days ahead of its usual schedule, and quickly advanced to cover the entire country by 28th June—well ahead of the normal timeline. The monsoon withdrawal began from western Rajasthan on 29th September, almost a month later than usual. Despite this delayed onset of withdrawal, the retreat was swift, with the monsoon withdrawing from most parts of northwest and adjoining central India by 1st October, and from major parts of the country outside the southern peninsula by 6th October. Rainfall activity persisted over the southern peninsula due to the presence of an active Inter-Tropical Convergence Zone (ITCZ) accompanied by embedded easterly wave disturbances. Following the southward shift of the ITCZ and a consequent decline in rainfall, the Southwest Monsoon finally withdrew from the entire country, including the Bay of Bengal and the Arabian Sea, on 21st October 2018, marking a delay of six days from the normal withdrawal date.

Actual onset and withdrawal dates of SW monsoon over Rajasthan 2019. The Southwest Monsoon advanced over Kerala on 1st June and reached Rajasthan by 2nd July. The monsoon withdrawal began from western Rajasthan on 11th October, significantly later than the normal withdrawal date of 15th September.

Actual onset and withdrawal dates of SW monsoon over Rajasthan 2020. The Southwest Monsoon advanced over Kerala on 1st June and reached Rajasthan on 24th June, slightly behind the normal schedule of 22nd June. The monsoon subsequently covered the entire state by 26th June, approximately 12 days earlier than the normal date of 8th July. The season began favourably with the formation and movement of Cyclone Nisarga over the Arabian Sea in the first week of June, which aided the monsoon's advance along the west coast. Favourable meteorological conditions further supported the timely progression of the monsoon. In Rajasthan, the monsoon entered through the Jodhpur, Udaipur, Kota, and Ajmer divisions on 24th June and rapidly covered the entire state by 26th June. The withdrawal of the monsoon commenced from western Rajasthan on 28th September, about 10 days later than the normal withdrawal date of 18th September, and the monsoon completely withdrew from the state by 6th October.

Actual onset and withdrawal dates of SW monsoon over Rajasthan 2021. The Southwest Monsoon advanced over Kerala on 3rd June and reached Rajasthan on 18th June, which was 8 days earlier than the normal schedule of 26th June. However, the monsoon covered the entire state by 13th July, about 5 days later than the normal date of 8th July. The season began positively in terms of rainfall, aided by the formation and movement of Cyclone Tauktae over the Arabian Sea during the second week of June. This system facilitated the monsoon's advance along the west coast into the mainland. Favorable subsequent atmospheric conditions supported the steady progress-sion of the monsoon. In Rajasthan, the Southwest Monsoon entered through the Udaipur and Kota divisions on 18th June and eventually covered the entire state and the country by 13th July, slightly behind the usual timeline.

Actual onset and withdrawal dates of SW monsoon over Rajasthan 2022. This year, the Southwest Monsoon advanced over Kerala on 29th May and reached Rajasthan on 30th June, which was 6 days later than the normal schedule of 24th June. However, the monsoon covered the entire state by 2nd July, approximately 6 days earlier than the normal date of 8th July. The isochrones depicting the progression of the monsoon in 2022 illustrate this pattern of delayed onset in Rajasthan followed by a rapid advance across the state.

Actual onset and withdrawal dates of SW monsoon over Rajasthan 2023. The Southwest Monsoon advanced to the South Andaman Sea and Nicobar Islands on 19th May, three days earlier than the normal date. However, its further progression was slow, with the

EQA 72 (2026): 65 - 73

DOI: 10.60923/issn.2281-4485/22641

monsoon setting in over Kerala on 8th June, seven days later than usual. Despite this delay, the monsoon covered the entire country by 2nd July, six days ahead of the normal date. The withdrawal of the monsoon from western Rajasthan commenced on 25th September, delayed by eight days compared to the typical schedule. The forecast for the monsoon onset over Kerala this year was accurate, marking the seventeenth consecutive correct forecast since 2005, except for 2015. The forecast predicted an onset date of 4th June, with a model error margin of ±4 days, closely matching the actual onset on 8th June.

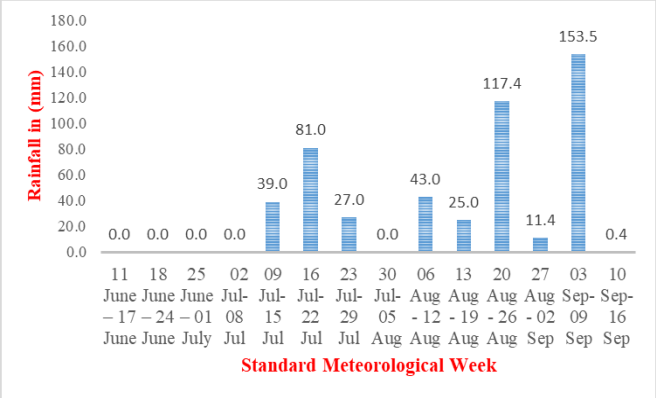

Figure 1. *Weekly rainfall distribution over Kota SW Monsoon 2018*

Rainfall distribution

Weekly rainfall distribution over Kota SW Monsoon 2018. The weekly rainfall distribution over Kota district in Rajasthan during the Southwest Monsoon season (June to September) of 2018 is illustrated in the Figure.1. The highest rainfall recorded in Kota district during the 2018 monsoon season was 153.5 mm, which occurred during the week of 3rd to 9th September. For most weeks throughout the season, the weekly rainfall was minimal, measuring less than 15 mm, except for seven weeks when rainfall amounts were more substantial.

Month wise rainfall distribution. During the 2018 monsoon season in Kota district, the highest daily rainfall recorded in June was 7.0 mm on 30th June, with a total monthly rainfall of 10.0 mm. In July, the highest daily rainfall was 48.0 mm on 19th July, contributing to a total monthly rainfall of 147.0 mm. August saw its peak daily rainfall of 74.6 mm on 22nd August, with a monthly total of 192.8 mm. The highest daily rainfall in September was 120.0 mm on 8th September, which was also the total rainfall recorded for the month (Tables 5 and 6).

Table 5. *Month wise Highest Rainfall recorded during southwest monsoon 2018 to 2023*

Year	June		July		August		Septembrr	
	Total mm	Highest Daily mm (Date)	Total mm	Highest Daily mm (Date)	Total mm	Highest Daily mm (Date)	Total mm	Highest Daily mm (Date)
2018	10	7.0 (30-06)	147	48.0 (19-07)	192.8	74.6 (22-08)	174	120.0 (08-09)
2019	60.3	58.0 (19-06)	506.6	85.0 (28-07)	632.5	140.0 (15-08)	172.7	65.0 (13-09)
2020	102.5	34.0 (22-06)	97.5	26.0 (15-07)	335.6	103.0 (18-08)	118.6	65.0 (03-09)
2021	0	0.0 (–)	233	75.0 (12-07)	843	209.0 (04-08)	121	20.0 (02-09)
2022	91.6	33.5 (20-06)	489.2	90.0 (23-07)	434.6	170.0 (23-08)	114	48.0 (10-09)
2023	162	40.0 (26-06)	505	60.0 (13-07)	48.2	26.5 (03-08)	125.7	34.8 (13-09)

Table 6. *Categories wise according IMD Monthly Rainfall Distribution Over Kota (June-September) 2018 to 2023.*

Rainfall Category	2018				2019				2020				2021				2022				2023			
	June	July	Aug	Sept	June	July	Aug	Sept	June	July	Aug	Sept	June	July	Aug	Sept	June	July	Aug	Sept	June	July	Aug	Sept
Very light	1.0	0.0	5.0	4.0	1.0	2.0	3.0	1.0	0.0	0.0	1.0	1.0	0.0	4.0	2.0	0.0	0.0	2.0	0.0	0.0	1.0	4.0	0.0	0.0
Light	2.0	6.0	7.0	4.0	0.0	2.0	4.0	6.0	5.0	5.0	4.0	0.0	0.0	6.0	5.0	10	4.0	9.0	17	5.0	0.0	6.0	4.0	6.0
Moderate	0.0	3.0	2.0	0.0	1.0	6.0	4.0	4.0	3.0	3.0	7.0	2.0	0.0	2.0	2.0	2.0	1.0	10.	3.0	2.0	5.0	13.	1.0	3.0
Heavy	0.0	0.0	1.0	0.0	0.0	4.0	1.0	1.0	0.0	0.0	1.0	1.0	0.0	1.0	4.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0
Very heavy	0.0	0.0	0.0	1.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0
Extremely heavy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

EQA 72 (2026): 65 - 73

DOI: 10.60923/issn.2281-4485/22641

Weekly rainfall distribution over Kota SW Monsoon 2019. The weekly rainfall distribution over Kota district in Rajasthan during the Southwest Monsoon season (June to September) of 2019 is illustrated in Figure 2,

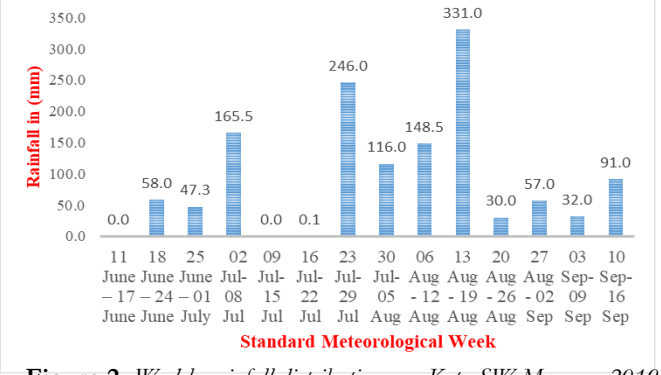

Figure 2. *Weekly rainfall distribution over Kota SW Monsoon 2019*

Month wise Rainfall Distribution

During the 2019 Southwest Monsoon season in Kota district, the highest daily rainfall recorded in June was 58.0 mm on 19th June, with a total monthly rainfall of 60.3 mm. In July, the maximum daily rainfall was 85.0 mm on 28th July, contributing to a total monthly rainfall of 506.6 mm. August experienced its peak daily rainfall of 140.0 mm on 15th August, with a monthly total of 632.5 mm. In September, the highest daily rainfall was 65.0 mm on 13th September, with a total monthly rainfall of 172.7 mm.

Weekly rainfall distribution over Kota SW Monsoon 2020. The weekly rainfall distribution over Kota district in Rajasthan during the Southwest Monsoon season (June to September) of 2020 is presented in Figure 3. The highest weekly rainfall recorded over Kota district in Rajasthan during the 2020 Southwest Monsoon season was 111.0 mm, occurring between 13th and 19th August. For most weeks of the season,

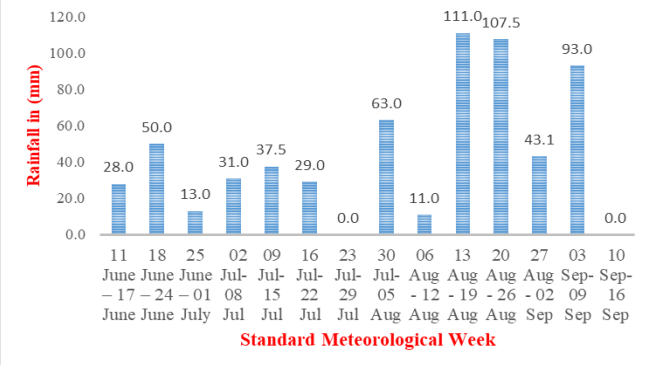

Figure 3. *Weekly rainfall distribution over Kota SW Monsoon 2020*

rainfall was minimal, with amounts less than 15 mm, except for ten weeks when the rainfall was more substantial.

Month wise Rainfall Distribution

During the 2020 Southwest Monsoon season in Kota district, the highest daily rainfall in June was 34.0 mm on 22nd June, with a total monthly rainfall of 102.5 mm. In July, the peak daily rainfall was 26.0 mm on 15th July, contributing to a total of 97.5 mm for the month. August experienced its highest daily rainfall of 103.0 mm on 18th August, with a total monthly rainfall of 335.6 mm. In September, the maximum daily rainfall was 65.0 mm on 3rd September, with a total rainfall of 118.6 mm for the month.

Weekly rainfall distribution over Kota SW Monsoon 2021. The weekly rainfall distribution over Kota district in Rajasthan during the Southwest Monsoon season (June to September) of 2021 is illustrated in Figure 4.

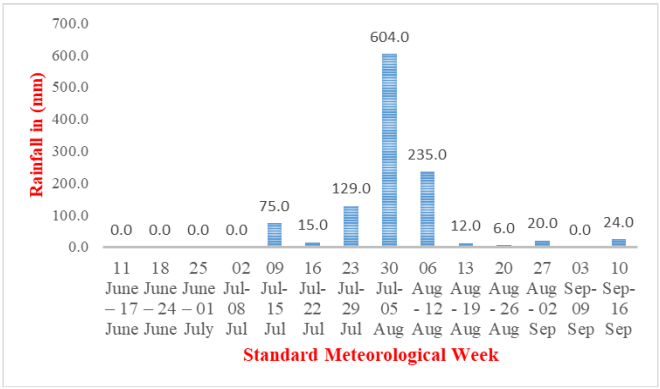

Figure 4. *Weekly rainfall distribution over Kota SW Monsoon 2021*

The highest weekly rainfall recorded over Kota district in Rajasthan during the 2021 Southwest Monsoon season was 604.0 mm, occurring between 30th August and 5th September. For most weeks of the season, rainfall was minimal, measuring less than 15 mm, except for seven weeks when rainfall amounts were significantly higher.

Month wise rainfall distribution

No rainfall was recorded during June 2021 in Kota district. The highest daily rainfall in July was 75.0 mm on 12th July, with a total monthly rainfall of 233.0 mm. August saw its peak daily rainfall of 209.0 mm on 4th August, contributing to a total monthly rainfall of 843.0 mm. In September, the maximum daily rainfall was 20.0 mm on 2nd September, with a total monthly rainfall of 121.0 mm.

EQA 72 (2026): 65 - 73

DOI: 10.60923/issn.2281-4485/22641

Weekly rainfall distribution over Kota** SW **Monsoon 2022. The weekly rainfall distribution over Kota district in Rajasthan during the Southwest Monsoon season (June to September) of 2022 is depicted in Figure 5-.

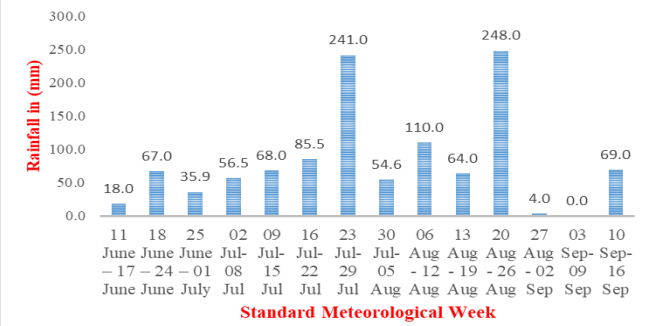

Figure 5: *Weekly rainfall distribution over Kota SW Monsoon 2022*

The highest weekly rainfall recorded over Kota district in Rajasthan during the 2022 Southwest Monsoon season was 248.0 mm, occurring between 20th and 26th August. For most weeks throughout the season, rainfall was minimal, measuring less than 15 mm, except for twelve weeks when rainfall amounts were notably higher.

Month wise rainfall distribution

During the 2022 Southwest Monsoon season in Kota district, the highest daily rainfall recorded in June was 33.5 mm on 20th June, with a total monthly rainfall of 91.6 mm. In July, the peak daily rainfall was 90.0 mm on 23rd July, contributing to a total monthly rainfall of 489.2 mm. August experienced its highest daily rainfall of 170.0 mm on 23rd August, with a monthly total of 434.6 mm. In September, the maximum daily rainfall was 48.0 mm on 10th September, with a total monthly rainfall of 114.0 mm.

Weekly rainfall distribution over Kota** SW **Monsoon 2023. The weekly rainfall distribution over Kota district in Rajasthan during the Southwest Monsoon season (June to September) of 2023 is presented in Figure 6. The highest weekly rainfall recorded over Kota district in Rajasthan during the 2023 Southwest Monsoon season was 132.0 mm, occurring between 25th June and 1st July. For most weeks throughout the season, rainfall was minimal, with amounts less than 15 mm, except for nine weeks when rainfall was considerably higher.

Month wise rainfall distribution

During the 2023 Southwest Monsoon season in Kota district, the highest daily rainfall recorded in June was

,

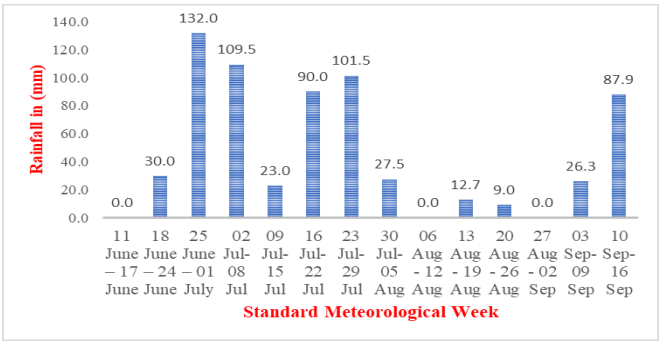

Figure 6. *Weekly rainfall distribution over Kota SW Monsoon 2023*

40.0 mm on 26th June, with a total monthly rainfall of 162.0 mm. In July, the peak daily rainfall was 60.0 mm on 13th July, contributing to a total monthly rainfall of 505.0 mm. August experienced its highest daily rainfall of 26.5 mm on 3rd August, with a total monthly rainfall of 48.2 mm. In September, the maximum daily rainfall was 34.8 mm on 13th September, with a total monthly rainfall of 125.7 mm.

Importance of rainfall

Water is the most crucial climatic factor influencing crop growth and development. Limited water availability often restricts plant development because water is essential for sustaining physiological and biochemical processes. It functions both as an energy exchanger and as a carrier of nutrients in solution within the plant. In regional agricultural production studies, rainfall is considered a factor of paramount importance (Doorenbos & Kassam, 1979). Schulze et al. (1997) emphasized that the analysis of rainfall should focus on both temporal and spatial patterns, including:

- Spatial distribution; how much rain falls and where it occurs.
- Seasonal distribution; the timing of rainfall throughout the year.
- Frequency; how often rainfall events occur.
- Duration and intensity; how long rainfall events last and how much water falls per unit time.

In India, rainfall is the primary source of soil moisture for crops, supplemented to a minor extent by dew and fog. However, not all rainfall becomes available to plants. A portion is intercepted by foliage before it reaches the ground; some is lost as surface runoff into streams; some infiltrates deeply beyond the reach of crop roots; and some evaporates directly from the soil surface without being transpired by plants (Schulze et al., 1997).

EQA 72 (2026): 65 - 73

DOI: 10.60923/issn.2281-4485/22641

Effect of rainfall on crop production. Water deficits reduce both leaf area development and delay or accelerate senescence, which in turn decreases net photosynthesis per unit leaf area. Generally, the water deficit required to affect photosynthesis is greater than that needed to slow leaf elongation (Turner and Begg, 1978). In barley, water stress during the vegetative stage primarily lowers yield by reducing leaf area and thus light interception. During the grain-filling stage, yield losses result almost equally from reduced photosynthesis per unit area due to early leaf senescence. Water deficits affect photosynthesis largely by reducing stomaatal conductance. In holm oak (*Quercus ilex*) seedlings, drought tolerance acquired through hardening is linked to lower osmotic potential, improved stomatal regulation, increased root growth capacity, and enhanced cell membrane stability (Farooq et al., 2009). Severe water deficits sufficient to close stomata also reduce dark respiration, although this reduction is generally less than the decrease in photosynthesis (Pagter, 2005). Short-term deficits do not affect photorespiration, but prolonged stress can lower it due to depletion of necessary substrates (Troughton and Slatyer, 1969).

Effect of rainfall distribution on crops. Variability in rainfall distribution, worsened by global warming, can disrupt planting schedules and reduce yields (Ugochukwu et al., 2000). Crop success depends not only on the total seasonal rainfall but also on its timing and distribution throughout the growing period (Igbekele, 1975).

Rainfall amount and crop performance. The quantity of rainfall and its seasonal distribution strongly influence crop growth and productivity. Even with normal annual totals, poor seasonal distribution can cause dry spells that stress crops (Barron et al., 2003). Rainfall is commonly measured in millimetres per day (mm/day), representing the total depth of rain collected over a 24-hour period.

Rainfall intensity and crop response. Rainfall intensity is the depth of water (mm) received during a rainfall event divided by the duration of that event (hours), expressed in mm/hour. High-intensity rainfall with large, forceful drops can be less beneficial for crops because it breaks down soil aggregates, causing surface sealing, reduced infiltration, and increased runoff—particularly in fine-textured soils (Simane & Struick, 1993). In contrast, low-intensity rainfall with smaller droplets allows more infiltration and reduces surface runoff.

Effective rainfall. Effective rainfall refers to the portion of total rainfall that remains in the root zone and is available for plant use (Walter, 1967). After rainfall, part of the water infiltrates into the soil, part remains on the surface, and part flows away as runoff. Surface water may evaporate, while infiltrated water either percolates beyond the root zone or is retained within it, where it can be absorbed by plants.

Mechanisms of crop adaptation

In natural environments, plants adapt to water deficit through a variety of morphological, physiological, and biochemical mechanisms. These may be short-term responses or long-term survival strategies such as early flowering in seasons with low rainfall (Bohnert et al., 1995; Basu et al., 2016). In C3 cereals like wheat and barley, phenological adjustments—especially early maturity—are effective in avoiding prolonged moisture stress (Lopes et al., 2011). Plants tolerant to waterlogging often develop traits and metabolic adjustments to survive oxygen shortages, such as:

- maintaining internal aeration via aerenchyma formation and creating oxidized zones around roots through radial O_2 loss (Armstrong et al., 1994);
- adjusting metabolism to sustain energy production under hypoxia, including storing carbohydrates for fermentation (Brandle, 1991).

Metabolic adaptations. Under oxygen deficiency, plants shift from aerobic respiration to anaerobic pathways, maintaining carbohydrate reserves, preventing cytoplasmic acidification, and activating antioxidant defenses (Davies, 1980; Drew, 1997). Glycolysis becomes the main energy source, requiring continuous regeneration of NAD^+ from NADH. Plant breeders have improved drought resistance in semi-arid and arid crops by selecting traits such as rapid grain filling and efficient assimilate transfer. These selections have yielded 3–11% higher production under dry conditions without yield loss in wetter years (Richards and Passioura, 1989; Whan et al., 1993).

Morphological adaptations. Reduced leaf area lowers transpiration and delays severe water stress (Mitra, 2001). Early senescence of lower leaves in cereals may conserve water without major yield penalties (Hall et al., 1979). Deeper rooting varieties generally perform better under drought (Hurd, 1974).

Physiological adaptations. Physiological mechanisms include:

- seed priming: pre-sowing hydration to enhance

EQA 72 (2026): 65 - 73

DOI: 10.60923/issn.2281-4485/22641

drought resistance (Henkel, 1961):
- stomatal regulation: closure reduces water loss (Shimshi, 1963);
- osmotic adjustment: maintaining turgor and photosynthesis under low water potential (Turner and Jones, 1980);
- osmotic adjustment may also improve reproductive success by maintaining pollen viability through reduced abscisic acid production (Morgan, 1980).

Drought escape. Drought escape is the ability of plants to complete their life cycle before severe water deficits occur. This is achieved through rapid phenological development such as early flowering and maturity. For example, early cowpea cultivars like 'Ein El Gazal' and 'Melakh' thrive in short rainy seasons by avoiding late-season drought (Hall, 2004).

Developmental mechanisms. Some species employ partial dormancy or phenological plasticity to survive dry years. Desert ephemerals, for example, germinate only after significant rainfall, develop rapidly, and produce seeds even in low-rainfall years (Mulroy and Rundle, 1977; Mittler et al., 2001).

Future prospects

Effective resource management is critical for adapting to variable rainfall patterns and maintaining crop productivity. Strategies such as optimizing planting schedules, improving water-use efficiency, and cultivating high-value crops can enhance resilience to climate change. By integrating these approaches, agriculture can remain both economically viable and environmentally sustainable in the face of increasing climatic uncertainty.

Conclusions

The analysis of southwest monsoon rainfall patterns in Kota district over the period 2007–2023 reveals considerable interannual variability, with notable deviations from the long-term average in both magnitude and distribution. Rainfall onset and withdrawal dates varied significantly, influencing the length of the effective growing season. Such variability directly impacts sowing windows, crop growth, and yields, particularly for rainfed crops. Years with early onset and well-distributed rainfall supported better crop performance, while delayed onset, prolonged dry spells, or excess rainfall during critical growth stages caused yield reductions. Understanding these rainfall characteristics enables more effective crop planning, irrigation scheduling, and risk management strategies..

Strengthening early warning systems and promoting adaptive agricultural practices are essential to enhance resilience against monsoon variability in the region.

References

BARRON J., ROCKSTRÖM J., GICHUKI F., HATIBU N. (2003) Dry spell analysis and maize yields for two semiarid locations in East Africa. Agricultural and Forest Meteorology, 117(1–2):23–37. https://doi.org/10.1016/S0168-1923(03)00037-6

BASU S., RAMEGOWDA V., KUMAR A., PEREIRA A. (2016) Plant adaptation to drought stress. F1000Research, 5:1554. https://doi.org/10.12688/f1000research.7678.1

BOHNERT H.J., NELSON D.E., JENSEN R.G. (1995) Adaptations to environmental stresses. The Plant Cell, 7(7):1099–1111. https://doi.org/10.1105/tpc.7.7.1099

BRANDLE J.R. (1991) Windbreaks in North American agricultural systems. Agronomy Journal, 83(6):993–999. https://doi.org/10.1023/B:AGFO.0000028990.31801.62

DAVIES W.J. (1980) Physiological aspects of drought resistance. In N. C. Turner & P. J. Kramer (Eds.), Adaptation of plants to water and high temperature stress (pp. 1–16).

DOORENBOS J., KASSAM A.H. (1979) Yield response to water (FAO Irrigation and Drainage Paper No. 33). Food and Agriculture Organization of the United Nations.

DREW M.C. (1997). Oxygen deficiency and root metabolism: Injury and acclimation under hypoxia and anoxia. Annual Review of Plant Physiology and Plant Molecular Biology, 48:223–250. https://doi.org/10.1146/annurev.arplant.48.1.223

FAROOQ M., WAHID A., KOBAYASHI N., FUJITA,D., BASRA S.M.A. (2009) Plant drought stress: Effects, mechanisms and management. Agronomy for Sustainable Development, 29(1):185–212. https://doi.org/10.1007/978-90-481-2666-8_12

HALL A.E. (2004) Breeding for adaptation to drought and heat in cowpea. European Journal of Agronomy, 21(4), 447–454. https://doi.org/10.1016/j.eja.2004.07.005

HALL A.E., SCHULZE E.D., LANGE O.L. (1979) Moderate water stress and plant water relations. Plant, Cell and Environment, 2(2):99–113.

HENKEL E.A. (1961) Root penetration studies in relation to soil moisture and aeration. Soil Science Society of America Journal, 25(5):386–389.

HURD E.A. (1974) Phenotype and drought tolerance in wheat. Agricultural Meteorology, 14(1–2):39–55. https://doi.org/10.1016/0002-1571(74)90009-0

IGBEKELE J.T. (1975) Crop water requirements in Nigeria.

DOI: 10.60923/issn.2281-4485/22641

Nigerian Agricultural Journal, 12(2):55–64.

LOPES M.S., REYNOLDS M.P., MANES Y. (2011) Genetic strategies for improving drought adaptation in cereals. Journal of Experimental Botany, 62(1):89–103.

MITRA J. (2001) Genetics and genetic improvement of drought resistance in crop plants. Current Science, 80(6): 758–763. https://www.jstor.org/stable/24105661

MORGAN J.M. (1980) Osmotic adjustment in Australian wheat varieties in relation to grain yield in a range of field environments. Australian Journal of Agricultural Research, 31(3):319–326.

MULROY T.W., RUNDEL P.W. (1977) Annual plants: Adaptations to desert environments. BioScience, 27(2):109–114. https://doi.org/10.2307/1297607

PAGTER M. (2005) Physiological responses of plants to drought stress. Horticultural Science, 40(2):67–77.

RICHARDS R.A., PASSIOURA J.B. (1989) A breeding program to reduce the diameter of the major xylem vessel in the seminal roots of wheat to improve grain yield in rain-fed environments. Australian Journal of Agricultural Research, 40(5):943–950. https://doi.org/10.1071/AR9890943

SCHULZE R.E., MEIGH J., HORAN M. (1997) Present and potential future water resources in South Africa. Water SA, 23(2):151–158.

SHIMSHI D. (1963) Effect of root temperature on transpiration and on water and ion uptake by intact plants. Physiologia Plantarum, 16(3):481–492.

SIMANE, B., & STRUICK, P. C. (1993). Agro-ecological analysis of barley landraces from the central highlands of Ethiopia. Netherlands Journal of Agricultural Science, 41(1): 1–18.

TURNER N.C., BEGG J.E. (1978) Responses of pasture plants to water deficits. In J. R. Wilson (Ed.), Plant relations in pastures CSIRO, 50-66. https://www.cabidigitallibrary.org/doi/full/10.5555/19780770795

TURNER N.C., JONES M.M. (1980) Turgor maintenance by osmotic adjustment: A review and evaluation. In N. C. Turner and P. J. Kramer (Eds.), Adaptation of plants to water and high temperature stress. Wiley, 87-103. https://www.cabidigitallibrary.org/doi/full/10.5555/19812607508

UGOCHUKWU E.N., ONWUEME I.C., EKANAYAKE I.J. (2000) Effect of water stress on the growth and yield of three cassava cultivars. Journal of Agricultural Science, 134(3):341–348.

WALTER H. (1967) Ecology of tropical and subtropical vegetation. Oliver and Boyd. https://journals.lww.com/soilsci/citation/1976/05000/Ecology_of_Tropical_and_Subtropical_Vegetation.13.aspx

WHAN B.R., CARLTON G.P., BYTH D.E. (1993) Breeding for drought resistance in grain sorghum. Australian Journal of Agricultural Research, 44(5):933–952.