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Climate-resilient crop adaptations in Rajasthan: Strategies to combat drought and heat stress

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Abstract
Rajasthan, characterized by arid and semi-arid climates, faces increasing challenges from drought and heat stress due to climate change. Climate-resilient crop adaptations are crucial for sustaining agricultural productivity in the region. This review explores strategic interventions, including the development and adoption of drought-tolerant crop varieties, improved irrigation methods, and climate-smart agronomic practices. Emphasis is placed on integrated water resource management, mulching, intercropping, and the use of indigenous knowledge. These adaptations not only enhance crop yield and water use efficiency but also build long-term resilience in farming communities, ensuring food security and livelihood sustainability in the face of climatic extremes.

Keywords: Climate-resilient crops, drought tolerance, heat stress, sustainable agriculture, water resource management

Introduction

The northwest Indian state of Rajasthan is situated between latitudes 23°3′ and 30°12′ N and longitudes 69°30′ and 78°17′ E. With an area of over 342.239 lakh hectares, or 10.41 per cent of India's total land area, it is the largest state in the nation (Reddy *et al*., 2018) [ ]. Approximately 179.03 lakh hectares of this are net sown, and 27.56 lakh hectares are wooded. The net irrigated area of the state is 78.8171 lakh hectares, while the gross irrigated area is 101.71 lakh hectares (Panda *et al*., 2019) [15].

Summer, monsoon, post-monsoon, and winter are the four distinct seasons that make up Rajasthan's primarily hot and arid climate. The summer months of April through June are marked by exceptionally high temperatures, usually between 32°C and 45°C (Guhathakurta *et al*., 2015) [6]. The temperature in the western desert regions can reach 48°C, especially during the months of May and June. The monsoon season, which brings with it significant humidity and a welcome dip in temperature, begins in late June and lasts until September. The south eastern parts receive approximately 1000 mm of rainfall annually, whereas the western desert zones receive as low as 150 mm (Moharana *et al*., 2016) [14].

Approximately 90 per cent of the rainfall occurs during the south-west monsoon, and depending on how dry the area is, there might be anywhere from 6 to 42 wet days. October and November are the post-monsoon season, when temperatures range from 18°C to 38°C. From December to March, this transitional phase precedes the winter season. The coldest month is usually January, when temperatures range from 4°C to 28°C. Sometimes it gets below freezing in desert or high-altitude regions like Mount Abu and Churu (IMD, 2017).

Rajasthan's economy depends heavily on agriculture, which faces tremendous problems due to the state's severe and unpredictable environment. Since most farming is rain fed here, periodic droughts and a decline in agricultural productivity are caused by the unpredictable monsoon rains (Bhati *et al*., 2017) [2]. These problems have been made worse by climate change; rising heat waves and unpredictable rainfall patterns are major concerns to food security. Climate-resilient crop types and sustainable agriculture methods must be developed and implemented immediately. In Rajasthan's fragile agro-ecological zones, these adaptation measures are essential for preserving livelihoods, increasing productivity, and ensuring resilience against climate uncertainties (Rathore & Verma, 2013) [17].

Climatic Challenges in Rajasthan

Rajasthan's climate ranges from arid in the west to semi-arid in the east, with annual rainfall varying between 50 to 500 mm, often unreliable (Bhati *et al*., 2017) [2]. Prolonged dry spells and heat waves result in soil moisture deficits, impairing crop growth and yield. According to the Indian Meteorological Department (IMD), average temperatures have risen by 0.6–1.2°C over the last 50 years in Rajasthan, exacerbating heat stress on crops (IMD, 2020). Drought affects nearly 60 per cent of Rajasthan's agricultural land; therefore, necessitating urgent interventions are required (Sharma *et al*., 2018) [23].

Interventions against Drought and Heat Stress

1.1. Drought-Tolerant Crop Varieties

Breeding and promoting drought-tolerant varieties is a fundamental approach. Crops like millet (Bajra), sorghum (Jowar), and pigeon pea (Arhar) are naturally adapted to Rajasthan's dry environment due to their deep root systems and efficient water use (Manga *et al*., 2015) [12]. Recent advances have produced improved cultivars with enhanced drought tolerance by incorporating traits such as osmotic adjustment, stomatal regulation, and early maturity (Sallam *et al*., 2019) [22]. For instance, drought-tolerant pearl millet varieties have shown stable yields under moisture deficit (Yadav *et al*., 2017) [29, 30]. Drought-tolerant varieties are shown in Table 1.

Table 1: Drought tolerance varieties in Rajasthan

S. No.	Crop	Notable Drought-Tolerant / Key Varieties	Special Features
1.	Wheat	Raj 3077, Raj 3765, Raj 3777, Raj 4037, Raj 4079	Tolerant to heat, salinity, late sowing, rust, and CCN; high

			Fe & Zn in Raj 4120
2.	Barley	RDB-1, BL-2, Rajkiran, RD 2624, RD 2660, RD 2715, RD 2786, RD 2794, RD 2899	Dwarf, salinity and rust resistant, dual-purpose (grain + fodder), for rainfed areas
3.	Chickpea	RSG 888, CSJ 515, RSG 973, RSG 963, CSJK 174, CSJK 21	Rainfed, early maturity, double pod, green seeds, bold seeded
4.	Mustard	Durgamani	Orobanche resistant
5.	Field Pea	RPG-3	High protein, powdery mildew resistant
6.	Pearl Millet	Raj 171, RHB 90, RHB 154, RHB 233, RHB 234	Downy mildew resistance, drought-tolerant, biofortified, suitable for arid zones
7.	Groundnut	RG 425, RG 382, RG 141, RG 638, RG 648, RG 575-1	Drought, disease resistant, high pod yield
8.	Clusterbean	RGC-936, RGC-1002, RGC-1033, RGC-1055, Karan Guar 1, 14, 15	High gum content, photo-insensitive, drought-tolerant
9.	Cowpea	RC 19, RC 101, RCV-7	Early maturity, grain and vegetable types
10.	Mungbean	RMG 62, RMG 268, RMG 344, RMG 492, RMG 975, MSJ 118	Early maturity, drought/web blight tolerant, short duration
11.	Muskmelon	Durgapura Madhu, RM 50, MHY 3, MHY 5	High sugar content, resistant to root rot, mildew, virus
12.	Watermelon	Durgapura Kesar, Durgapura Lal	Saffron/dark red flesh, high sweetness
13.	Onion	RO-1, RO-59, RO-252	Suitable for rabi and kharif; high bulb quality

Source: https://raridurgapura.org/varieties-developed.htm

1.2. Heat-Tolerant Crops and Genotypes

Heat stress affects flowering, pollination, and grain filling, reducing yield significantly (Arshad *et al*., 2017) [1]. Heat-tolerant cultivars of wheat and mustard have been developed with traits such as heat shock protein production and cellular membrane stability (Wahid *et al*., 2007) [28]. Incorporating genetic markers linked to heat tolerance facilitates marker-assisted selection in breeding programs targeting Rajasthan's hot climate (Singh *et al*., 2014) [25]. Heat-tolerant varieties are shown in Table 2.

Table 2: Heat tolerance varieties in Rajasthan

S. No.	Crop	Variety/Genotype	Key Features
1	Wheat	Raj 1482	Known for superior quality characteristics
2		Raj 3077	High yield; suitable for timely/late sowing and saline/alkaline soils
3		Raj 3765, Raj 3777	Tolerant to high temperature and rusts; suitable for normal to late sowing
4		Raj 4037, Raj 4083, Raj 4079	Highly heat-tolerant; ideal for warmer areas
5	Indian Mustard	BPR-349-9, Urvashi, BPR-541-2, BPR-605-40, Pusa Tarak, RGN-48, BPR-549-2, DRMR-729, DRMR-1918	Identified as heat-tolerant at seedling stage
6	Barley	RD-2660, RD-2052, RD-2715, RD-2794	Genotypes with desirable grain yield under heat stress

Source: https://raridurgapura.org/varieties-developed.htm

Agronomic and Management Strategies

1.1. Conservation Agriculture

Conservation agriculture (CA) is a sustainable farming method that aims to enhance productivity while preserving natural resources. It is based on three principles: minimal soil disturbance, permanent soil cover, and crop diversification. Minimal tillage reduces soil erosion, while crop rotation and diversification improve soil fertility and yields (Hobbs, 2007) [8]. Other strategies include integrated nutrient and pest management, precision irrigation, and climate-resilient crop varieties. CA enhances carbon sequestration, water-use efficiency, and resilience against climate change. It reduces input costs while maintaining or increasing yields, making it economically viable for farmers. Promoting training, policy support, and community participation is crucial for the wider adoption of CA practices for long-term agricultural sustainability and food security. These practices improve soil moisture retention and organic matter, enhancing resilience to drought (Mitchell *et al*., 2019) [13].

Source: https://www.biotecharticles.com/Agriculture Article/Integrated-Nutrient-Management

Fig 1

1.2. Efficient Water Management

Rajasthan's arid climate, low rainfall, and frequent droughts necessitate efficient water management. Key strategies include micro-irrigation systems like drip and sprinkler irrigation, traditional rainwater harvesting methods, watershed development programs, crop diversification to less water-intensive and drought-tolerant crops, remote sensing and GIS for monitoring water bodies, and community participation (Pathak *et al.*, 2013) [16]. These strategies aim to ensure sustainable water use and improve agricultural resilience in water-scarce regions. Rainwater harvesting structures like check dams and farm ponds supplement irrigation during dry spells. Scheduled irrigation aligned with crop phenology maximizes water use efficiency and reduces stress impacts (Reddy *et al.*, 2012) [20]. Awareness campaigns and community participation are crucial for the success of these initiatives. Overall, these strategies aim to ensure sustainable water use and improve agricultural resilience in Rajasthan's water-scarce regions (Tiwari, K., Goyal, R., Sarkar, A., & Munoth, P. (2015) [27]. Integrated water resources management with special reference to water security in Rajasthan, India. *Discovery*, *41*(188), 93-101. *et al.*, 2015; Gupta, 2014) [7].

Source: https://flotaa.com/water-conservation-in-agriculture/

Fig 2

1.3. Crop Diversification and Intercropping

Crop diversification and intercropping are crucial for agricultural sustainability in Rajasthan, a state prone to erratic rainfall and frequent droughts. Diversifying crops like bajra, pulses, oilseeds, and fodder improve soil health and reduces crop failure risk. Intercropping systems like bajra-moth bean, guar-mungbean, and sesame-clusterbean maximize land use and income per unit area, while maintaining soil fertility and reducing pest incidences. Adopting drought-tolerant varieties enhances resilience in arid and semi-arid regions (Khan, & Yadav, 2017) [9, 29, 30]. Crop diversification supports market stability by reducing over-dependence on a single crop (Rathore *et al.*, 2011) [18]. Integrated strategies combining legume intercropping and agroforestry practices are increasingly promoted under government and ICAR initiatives. Growing multiple crops and intercropping systems also enhance resilience by reducing risk exposure and spreading labor and income, reducing farmers' vulnerability (Sachan, & Choudhary, 2019) [21].

Source: https://www.sketchbubble.com/en/presentation-crop-diversification.html

Fig 3

1.4. Use of Bio-fertilizers and Soil Amendments

Soil amendments and biofertilizers are essential for sustainable agriculture in Rajasthan, which has dry and semi-arid climates. Biofertilizers like *Rhizobium*, *Azotobacter*, *Azospirillum*, and phosphate-solubilizing bacteria increase nutrient availability, soil fertility, and reduce reliance on chemical fertilisers. Green manures and vermin-compost increase organic matter and water retention in sandy soils (Srivastava *et al.*, 2010) [26]. Gypsum and lime are used in saline-alkaline regions to improve pH balance and structure, promoting crop development. These eco-friendly approaches support climate-resilient farming, restore degraded soils, and contribute to long-term agricultural sustainability in Rajasthan's fragile agro-ecosystems. Krishi Vigyan Kendras (KVK) and government initiatives are educating farmers about the benefits of managing soil health and using bio-inputs (Dubey *et al.*, 2019) [3].

Source: https://www.linkedin.com/pulse/unlocking-soil-potential-power-biofertilizers-edward-scott-ia85f

Fig 4

Mitigation strategies and Modern Farming Practices in Rajasthan

Rajasthan is implementing mitigation strategies and modern farming practices to tackle climate change, water scarcity, and land degradation. Techniques like drip and sprinkler irrigation conserve water in arid regions, while climate-resilient crop varieties like pearl millet and cluster bean are promoted (Maheswari, 2019) [11].

Fig 2: Organic, Natural, and Chemical Farming Practices (Ranjit Kumar S. K., 2020)

Mitigation strategies in agriculture focus on reducing environmental impacts while maintaining productivity. Organic and natural farming emphasize sustainability, using compost, bio-fertilizers, and crop rotation to improve soil health and reduce greenhouse gas emissions. In contrast, chemical farming relies heavily on synthetic fertilizers and pesticides, which can degrade soil and pollute water sources. Modern farming practices, including precision agriculture and drip irrigation, enhance resource efficiency and yield. While chemical farming offers short-term gains, organic and natural methods support long-term resilience (Singh, 2009) [24]. Comparing these, organic and natural farming align better with climate mitigation goals, promoting biodiversity, carbon sequestration, and eco-friendly food production systems shown in Figure 2. Some new interventions are essential for regions facing water scarcity and climate variability, as adopted in Rajasthan.

Challenges and Future Perspectives

Despite progress, challenges such as limited access to improved seeds, inadequate irrigation infrastructure, and socio-economic constraints impede widespread adoption of climate-resilient strategies in Rajasthan (Eggermont *et al*., 2015) [5]. Extension services and policy support must prioritize farmer awareness and capacity building. Integrating traditional knowledge with modern science offers promising avenues for sustainable adaptation (Davis *et al*., 2010) [3].

Future research should focus on multi-stress tolerant crop varieties, considering combined drought and heat effects, and on developing affordable, scalable technologies suited to smallholder farmers. Climate-smart agricultural practices that improve soil health, enhance water efficiency, and support biodiversity conservation will be crucial for long-term resilience.

Conclusion

Rajasthan's vulnerability to drought and heat stress poses significant risks to agriculture and livelihoods. Climate-resilient crop adaptations, encompassing improved varieties, conservation agriculture, efficient water management, and biotechnological advances, present effective strategies to combat these challenges. Strengthening research, extension, and policy frameworks can facilitate widespread adoption of these practices, ensuring sustainable agricultural productivity and food security in this fragile environment.

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