

ADVANCEMENT IN DROUGHT PHYSIOLOGY OF RICE: A RESEARCH CONTINUUM FROM GENOTYPIC SELECTION TO GENOMIC PRECISION AT ICAR-CRRI, CUTTACK



Milan Kumar Lal, Koushik Chakraborty, Padmini Swain,
Bandana Mohapatra, MJ Baig



ICAR-Central Rice Research Institute (CRRI)
Cuttack-753006, Odisha, India

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Preface

Rice (*Oryza sativa* L.) is fundamental to food and nutritional security, particularly in Asia, where it supports millions of livelihoods. However, increasing climate variability, especially drought, poses a serious threat to sustainable rice production. Addressing this challenge requires a comprehensive understanding of the physiological and genetic mechanisms governing drought tolerance.

This research bulletin, "Three Decades of Drought Physiology in Rice: A Research Continuum from Varietal Screening to Genomic Precision at ICAR-CRRI, Cuttack," presents a systematic synthesis of drought-related research conducted at ICAR-Central Rice Research Institute over the past six decades. The work traces the evolution of scientific approaches from early varietal screening and identification of key physiological traits such as relative water content and root depth, to advanced molecular breeding involving QTL mapping, marker-assisted selection, and genome-wide association studies. The bulletin highlights significant progress in integrating physiology with breeding, leading to the development of drought-tolerant rice varieties such as Sahbhagidhan and CR Dhan series. It also captures emerging research directions, including microbiome-assisted resilience, physiological mitigation through compounds like melatonin, and the use of high-throughput phenomics and systems modeling.

A key strength of this compilation lies in its long-term experimental data and field validation, which have enabled consistent tracking of genetic gains and refinement of selection strategies. The convergence of physiological insights with genomic tools reflects a paradigm shift toward climate-smart rice research.

This bulletin is the outcome of sustained collaborative efforts by scientists and technical staff of ICAR-CRRI. It is intended to serve as a valuable resource for researchers, breeders, students, and policymakers engaged in developing resilient rice production systems. We hope that the insights presented will contribute to strengthening food security under changing climatic conditions.

(Authors: MK Lal, K Chakraborty, P Swain, B Mohapatra, MJ Baig)

ICAR-CRRI, Cuttack, Odisha

April 2026

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1: Introduction: Rice Production Systems, Drought Constraints, and the Scientific Basis for Breeding Drought-Tolerant Varieties

1.1 Rice as a Global Food Security Crop: Production Trends and Future Demand Projections

Rice (*Oryza sativa* L.) occupies a singular position in the global food system. As the primary dietary staple for more than 3.5 billion people, particularly across South Asia, Southeast Asia, and Sub-Saharan Africa, it provides a higher share of total caloric intake than any other cereal crop. Rice accounts for approximately 23% of per capita energy supply worldwide, with its significance rising to as high as 65-70% of total caloric intake in rice-dependent populations of South and Southeast Asia (Hassan et al., 2023; Shah et al., 2024). Globally, rice is cultivated on approximately 167 million hectares, with annual paddy production exceeding 755 million tonnes, a threefold increase from the 215 million tonnes recorded in 1961 (Rahman et al., 2023).

Asia remains the epicentre of global rice production, accounting for approximately 89% of total harvested area and contributing the majority of the world's supply (Hinjmans, 2023). India alone cultivates rice across approximately 43.7 million hectares, making it the world's second largest producer and the largest exporter, with annual exports exceeding 10 million tonnes, contributing significantly to national agricultural income (Samal et al., 2023). Despite these production achievements, projections by the Food and Agriculture Organization of the United Nations (FAO) indicate that global rice production must increase by approximately 5 million tonnes per year to meet the food security needs of a world population expected to reach 9.7 billion by 2050 (FAO 2023).

1.2 Drought Stress in Rice: Magnitude, Economic Impact, and Implications for Breeding Priority Setting

Drought is universally recognised as the single most damaging abiotic stress in global crop production, responsible for greater annual yield losses than all other environmental stresses combined (Kumar et al., 2024). In rice, the impacts of drought are both widespread and economically devastating. The rainfed lowland rice system of Asia, which alone encompasses approximately 45 million hectares, nearly 30% of the total global rice area, is estimated to experience frequent and significant drought stress affecting 19 to 23 million hectares annually (Haefele et al., 2009).

Yield losses attributable to drought in rice are profound and scale with stress severity. Mild drought conditions reduce grain yield by approximately 31-64%, while severe drought episodes cause yield reductions of 65-85% relative to well-watered controls (Kumar et al., 2008). In particularly severe years, drought stress leads to near-complete crop failure across large contiguous areas, forcing millions of smallholder farmers in rainfed systems into acute food insecurity and economic distress. Average yield reduction in rainfed, drought-prone rice areas has been documented in the range of 17% to 40% in severe drought years (FAO 2023).

Key Statistics: Drought affects an estimated 19-23 million hectares of rainfed lowland rice in Asia annually, with yield losses ranging from 17% under moderate stress to near-complete failure under severe conditions placing the livelihoods of more than 100 million smallholder farm households at risk (Haefele et al., 2009; Kumar et al., 2008).

Beyond immediate yield losses, drought stress also compromises rice grain quality. Drought at the grain-filling stage increases the proportion of chalky kernels and reduces milling recovery, thereby lowering market value and diminishing nutritional quality (Zhang et al., 2019). These compounded effects reduced yield quantity, degraded grain quality, and erosion of farm incomes underscore the critical importance of developing drought-tolerant rice varieties and characterising the physiological mechanisms underpinning drought adaptation.

1.3 Physiological and Biochemical Basis of Drought Stress: Key Traits and Mechanisms for Selection

Morpho-physiological Responses

Drought stress inflicts a complex and multi-dimensional cascade of morpho-physiological injuries on the rice plant (Mishra et al., 2024). At the morphological level, water deficit inhibits seed germination, restricts seedling establishment, reduces leaf area index, causes leaf rolling and early senescence, suppresses tillering capacity, and ultimately curtails biomass accumulation. Drought stress lowers plant height, stem diameter, and panicle length, while simultaneously increasing spikelet sterility and reducing 1000-grain weight (Kumar et al., 2024).

At the physiological level, drought stress disrupts cellular water relations through a reduction in relative water content (RWC), leaf water potential, and osmotic potential. The consequent loss of turgor pressure leads to stomatal closure, which restricts CO₂ entry and substantially reduces the rate of photosynthesis (Chen et al., 2025). Constrained photosynthetic carbon assimilation reduces the supply of carbohydrates to developing panicles, contributing directly to unfilled grains and reduced harvest index. Measurements of photosynthetic rate, transpiration rate, and instantaneous water use efficiency (WUE) have served as foundational physiological criteria for drought tolerance assessment in rice research programmes (Zhang et al., 2019).

Biochemical and Molecular Stress Responses

At the biochemical level, drought stress induces substantial oxidative damage through the generation of reactive oxygen species (ROS), including superoxide radicals (O₂⁻), hydrogen peroxide (H₂O₂), and hydroxyl radicals (OH•). These ROS species promote oxidative damage to cell membranes, proteins, and nucleic acids, causing further deterioration of photosynthetic machinery and cellular function (Kumar et al., 2024). As a counter-measure, drought-tolerant rice genotypes activate both enzymatic antioxidant defence systems including superoxide dismutase (SOD), catalase (CAT), ascorbate peroxidase (APX), and peroxidase (POD) and non-enzymatic osmoprotectants such as proline, polyamines, glycine

betaine, and soluble sugars (Ali et al., 2021). These osmoprotectants lower cellular osmotic potential, facilitating continued water uptake and turgor maintenance during moderate stress periods.

At the molecular signalling level, abscisic acid (ABA) functions as the primary drought stress hormone, initiating signal transduction cascades through the PYR/PYL/RCAR receptor complex, SnRK2 kinases, and downstream transcription factors (Li and Wang 2024). ABA regulates stomatal aperture through guard cell ion channels, activates stress-responsive gene networks, and coordinates osmotic adjustment and antioxidant responses. The MAPK and Ca^{2+} signalling pathways serve as key secondary messengers in amplifying and integrating the drought response at the cellular and whole-plant levels (Li and Wang 2024).

Growth-Stage Sensitivity to Drought

The sensitivity of rice to drought stress varies markedly across developmental stages, with the reproductive stage encompassing booting, anthesis, and early grain filling consistently identified as the most critical period for yield determination (Waqas et al., 2022). Drought imposed at the pre-anthesis and anthesis stages disrupts pollen viability, delays or suppresses floret opening, reduces spikelet fertility, and impairs grain filling, resulting in the most severe and economically damaging yield reductions. Studies have documented that drought stress at the flowering stage reduced grain yield by 23-24% even in improved hybrid rice cultivars, while simultaneously disrupting multiple physiological processes that did not recover to normal levels during grain filling (Zhang et al., 2019).

Three principal drought adaptation strategies have been identified in rice: (i) **drought escape**: rapid phenological development to complete the reproductive cycle before the onset of terminal drought; (ii) **drought avoidance**: maintenance of high tissue water potential through deep root systems, efficient stomatal regulation, and reduced cuticular water loss; and (iii) **drought tolerance**: the capacity to sustain metabolism and reproductive success even when tissue water deficits develop, through osmotic adjustment and antioxidant defence (Mishra et al., 2024; Ali et al., 2021). A fourth strategy **recovery** describes the ability to resume growth and reproductive activity after a transient drought, which is particularly relevant for rainfed systems experiencing intermittent dry spells (Hassan et al., 2023).

1.4 Breeding Approaches for Drought Tolerance: From Conventional to Molecular

Developing drought-tolerant rice varieties through breeding represents one of the most practical and cost-effective approaches to mitigating drought-induced yield losses at scale. However, breeding for drought tolerance is acknowledged as a formidable challenge due to the complex, polygenic, and environment-dependent nature of the trait, as well as the negative genetic correlations that frequently exist between drought tolerance and yield potential under well-watered conditions (Hassan et al., 2023).

Conventional breeding approaches based on empirical varietal evaluation under managed drought stress environments identified the first generation of drought-tolerant rice varieties, several of which including

Vandana, Sahbhagidhan (DRR Dhan 42), and Annada remain important in the upland rice cropping systems of India and Southeast Asia (Hassan et al., 2023; Samal et al., 2023). The establishment of national and international drought breeding networks including the Stress-Tolerant Rice for Africa and South Asia (STRASA) programme led by IRRI systematically expanded the scale and rigour of managed-stress screening, enabling identification of broadly adapted drought-tolerant genotypes across diverse environments.

The advent of molecular marker technologies transformed the landscape of drought tolerance research. Quantitative trait loci (QTLs) directly linked to grain yield under drought designated the *qDTY* series (Drought Yield QTLs) represented a landmark achievement in rice stress physiology and genomics. Major QTLs including *qDTY1.1*, *qDTY2.1*, *qDTY3.1*, *qDTY6.2*, and *qDTY12.1* have been fine-mapped, validated in near-isogenic line (NIL) backgrounds, and deployed in marker-assisted backcrossing programmes to develop improved varieties with significant yield advantages under stress conditions (Hassan et al., 2023; Ali et al., 2021).

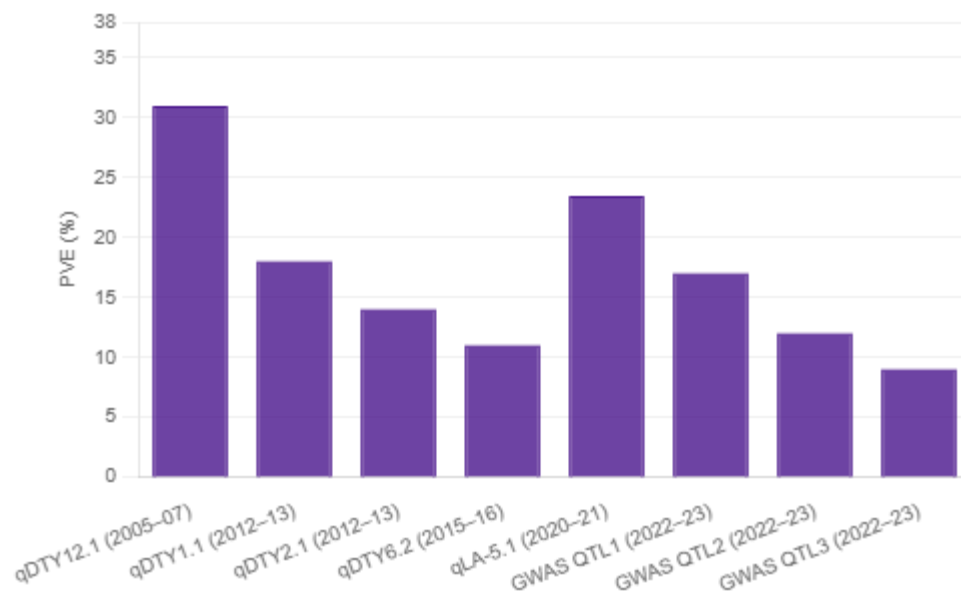


Fig. 1. Phenotypic variance explained (PVE %) by major drought-yield QTLs (*qDTY* series) mapped at ICAR-CRRI (2005-2023): a reference guide for prioritising QTL targets in marker-assisted selection and gene pyramiding strategies for drought-tolerant rice improvement.

More recently, genome-wide association studies (GWAS) conducted on large rice diversity panels have dissected the genetic architecture of drought tolerance at unprecedented resolution, identifying superior alleles distributed across multiple subpopulations of the 3K Rice Genome Panel (Hassan et al., 2023). Simultaneously, the development of CRISPR-Cas9 genome editing tools, high-throughput AI-assisted phenomics platforms, and genomic prediction models integrating multi-omics data represent the current

frontiers of drought tolerance research, promising to substantially accelerate the development of climate-resilient rice varieties (Chen and Liu 2025).

1.5 ICAR-CRRI, Cuttack: Institutional Infrastructure and Research Legacy Supporting Drought Physiology and Breeding

ICAR-Central Rice Research Institute (ICAR-CRRI), established on 23 April 1946 at Cuttack, Odisha, represents India's premier rice research institution and one of the world's most comprehensive rice research centres (CRRI Annual report 1994-2024). Founded in direct response to the devastating 1942 brown spot epidemic and the consequent Great Bengal Famine of 1943, the Institute was mandated from its inception to advance all aspects of rice science in service of India's food security (ICAR-NRRI. 2019). Over nearly eight decades of operation, ICAR-CRRI has developed more than 133 high-yielding rice varieties adapted to diverse agroecosystems, spanning irrigated, rainfed lowland, upland, semi-deepwater, flood-prone, and coastal saline environments (Melandri et al., 2019). Geographically, ICAR-CRRI is strategically located in Odisha – a state that epitomises the complex abiotic stress environment confronting rainfed rice farmers in eastern India. Odisha experiences among the most erratic monsoon patterns in the country, with frequent dry spells during the kharif season exposing millions of hectares of rainfed rice to episodic and terminal drought stress. The Institute's field stations and rain-out shelter facilities thus provide an ecologically relevant and methodologically rigorous platform for conducting drought physiology research under naturally variable and experimentally controlled stress conditions.

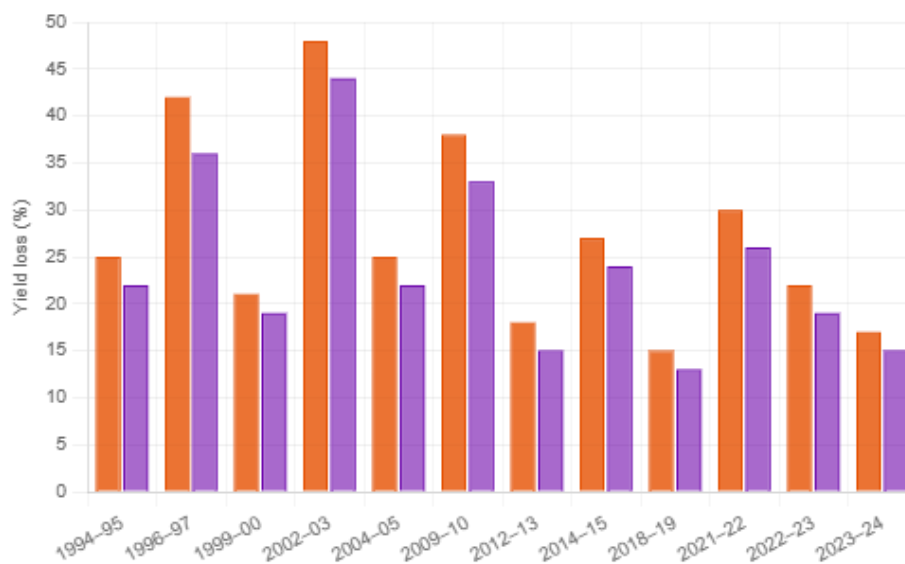


Fig. 2: Comparative yield loss (%) in upland versus rainfed lowland rice ecosystems during documented drought years at ICAR-CRRI: a baseline dataset for ecosystem-specific breeding target setting and contingency planning in eastern India.

The collaborative ties between ICAR-CRRI and the International Rice Research Institute (IRRI) formalised through a Memorandum of Understanding in 1974 and periodically renewed have been instrumental in integrating global scientific advances with the Institute's drought research programme (IRRI 2011). These partnerships facilitated the introduction of advanced molecular tools, international germplasm, and managed-stress evaluation methodologies that significantly elevated the scientific rigour and impact of CRRI's drought research in the post-2000 era.

From the earliest upland varietal trials in 1961 which provided the first quantitative evidence of genotypic variability in drought tolerance in Indian rice germplasm through the application of radioactive P^{32} tracer techniques for root distribution analysis in the 1970s to the deployment of genome-wide association studies and chromosome segment substitution lines in the 2020s, ICAR-CRRI has maintained a continuous and evolving programme of drought physiology research spanning six decades. This programme uniquely documents the full scientific trajectory of drought tolerance research in rice from empirical field observation to quantitative physiological genomics.

The present bulletin compiles and synthesizes this body of research, organized chronologically and thematically, to provide a coherent scientific narrative. It is intended to serve as both an institutional archive and a scientific reference for researchers, breeders, extension professionals, and policymakers engaged in climate-resilient rice improvement.

2: Drought-Tolerant Rice Varieties Released by ICAR-CRRI (1994-2024): Parentage, Adaptation, and Deployment Potential Across Agroecosystems

Over the past three decades, ICAR-CRRI has developed and released a series of rice varieties specifically targeting drought-prone and water-limiting agroecosystems across India. These varieties represent the applied outcome of the Institute's drought physiology and breeding programmes, combining early maturity (drought escape), deep root architecture (drought avoidance), and cellular water retention capacity (drought tolerance). Sahbhagidhan (released 2009/2011) stands as the most significant achievement of CRRI's drought breeding programme in the last 30 years (Swain et al., 2017). Developed in collaboration with IRRI, BAU, IGKV, and NDUAT through the Upland Rice Stress Breeding Network (URSN), it became the first variety explicitly bred for drought tolerance to receive national recognition and large-scale promotion through the National Food Security Mission (NFSM) minikits programme (2010).

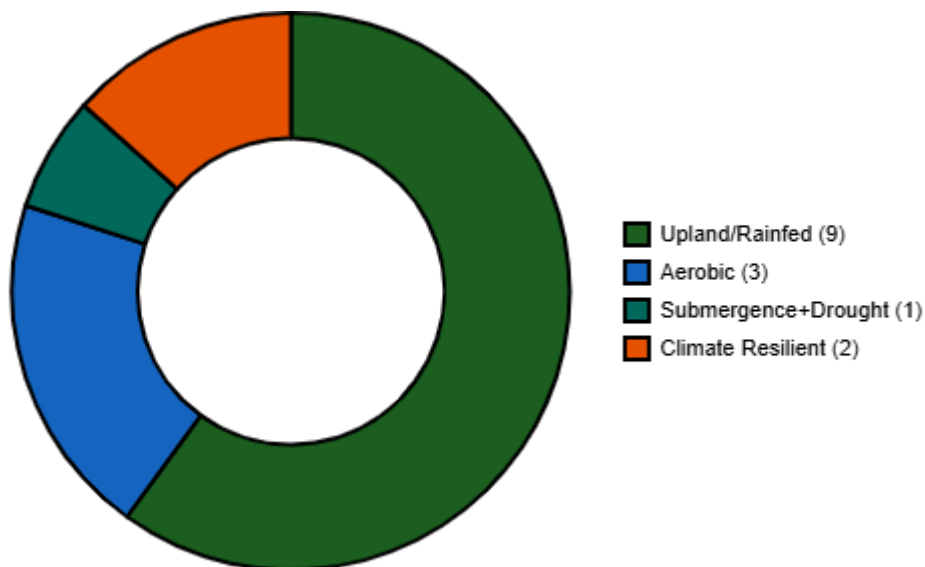


Fig. 3. Distribution of drought-tolerant rice varieties released by ICAR-CRRI (1990-2024) across target ecosystems (upland, rainfed lowland, aerobic, and climate-resilient): a reference for identifying ecosystem gaps and directing future varietal development priorities.

The variety has since been adopted by millions of farmers across Jharkhand, Odisha, Bihar, Chhattisgarh, and Uttar Pradesh. The 2024 release of CR Dhan 108 and CR Dhan 416 represents the Institute's latest contribution – climate-resilient varieties designed to withstand multiple abiotic stresses including drought, extreme temperatures, and erratic rainfall, launched by the Prime Minister of India in the context of the National Mission for Climate Resilient Agriculture.

Table 1: Drought-tolerant rice varieties released by ICAR-CRRI/ICAR-NRRI, Cuttack (1990-2024), with ecosystem, maturity, yield potential, and tolerance characteristics: a ready reference for breeders, extension agencies, and policymakers for selecting suitable parental lines and recommending varieties for drought-prone agroecologies

Variety Name	Ecosystem	Year Released	Duration (days)	Plant Ht. (cm)	Yield (t/ha)	Drought Tolerance	Recommended States/Region
Vandana (RR 167-982)	Upland / Rainfed	1992 / 2002	90-95	95-110	3.5	Drought, soil acidity	Odisha, Chhotanagpur Plateau
Annada (CR 1009)	Upland / Rainfed	1995	100-105	100-110	3.0-3.5	Drought escape (early)	Eastern India
Kalinga III	Upland	1997	95-100	90-100	2.8-3.2	Drought, soil acidity	Odisha, Jharkhand
Khandagiri	Upland / Rainfed	2000	90-95	85-95	2.5-3.0	Early drought	Odisha

Variety Name	Ecosystem	Year Released	Duration (days)	Plant Ht. (cm)	Yield (t/ha)	Drought Tolerance	Recommended States/Region
Kamesh (CR Dhan 40)	Bunded/Rainfed Upland	2008	110	100-110	3.0-3.5	Drought (vegetative)	Jharkhand, Maharashtra
Sahbhagidhan (IR 74371-70-1-1)	Upland / Rainfed	2009 / 2011	100	85-90	3.8-4.5	High drought tolerance	All India (upland)
Pyari (CR Dhan 200)	Aerobic / Water-limiting	2011	115-120	90-100	4.0	Water-limiting conditions	Odisha
CR Dhan 201	Aerobic / Water-limiting	2012	110-115	100-110	3.8	Aerobic drought	Bihar, Chhattisgarh
CR Dhan 202	Aerobic / Water-limiting	2012	110	95-105	3.7	Aerobic / terminal drought	Jharkhand, Odisha
Satyabhama (CR 2340-11)	Upland Drought-prone	2012	105-110	100-110	2.8 (drought) / 4.7 (normal)	Drought at reproductive stage	Odisha
CR Dhan 305	Shallow Rainfed Lowland	2016	120-125	100-110	4.5-5.0	Early drought escape	Jharkhand
BVD-109	Upland	2018*	95-100	90-100	2.15 (drought stress)	Reproductive drought	Eastern India
CR Dhan 801	Submergence + Drought	2020	120-125	100-105	4.5-5.5	Submergence + drought	Flood-prone lowlands
CR Dhan 108	Climate Resilient	2024	110-115	95-105	3.8-4.5	Drought + extreme weather	Odisha, Eastern India
CR Dhan 416	Climate Resilient	2024	105-110	90-100	3.5-4.2	Drought tolerance	Eastern India

Source: ICAR-CRRI Popular Varieties page (icar-crrl.in); ICAR-NRRI Achievement Book (2019); AICRIP Centers Report (Cuttack); CRRI Annual Reports 1992-2024. Yield values represent performance under drought/water-limiting conditions unless otherwise stated.

3: Germplasm Screening and Physiological Studies (1995-2024): Identification of Donor Lines, Tolerance Traits, and Selection Criteria for Drought Breeding

Systematic screening of rice germplasm under managed drought stress conditions has been a cornerstone of CRRI's drought research programme for three decades. Beginning with physiological screening using RWC and transpiration rate in the mid-1990s, and progressively advancing to managed stress rain-out shelter facilities capable of imposing precise soil water potentials (-40 to -70 kPa), CRRI has evaluated thousands of genotypes over 30 years. The institute screens approximately 35 AICRIP

trials each year across multiple ecosystems, maintaining one of the most extensive single-institution germplasm evaluation records in Asia.

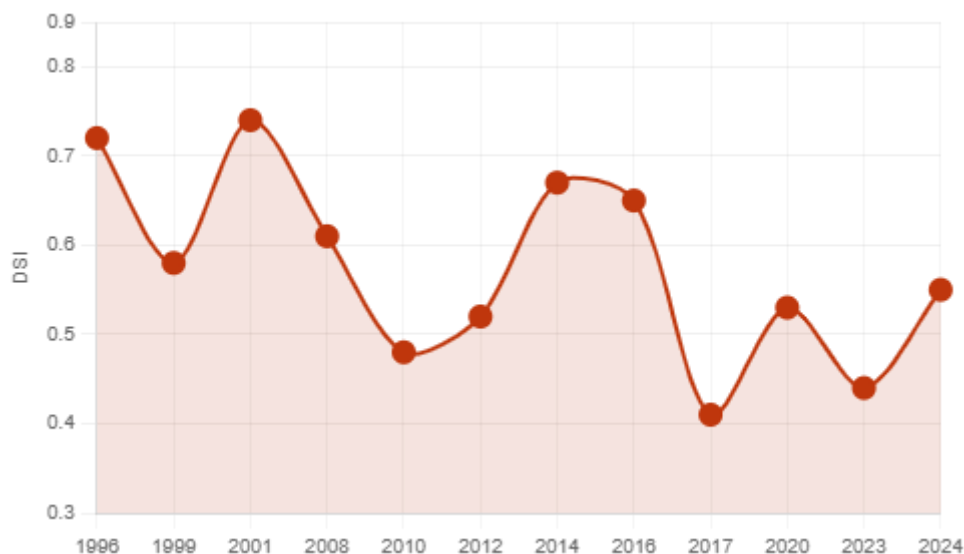


Fig. 4. Temporal trend in Drought Susceptibility Index (DSI) of key rice genotypes evaluated at ICAR-CRRI over three decades: evidence of cumulative genetic gain in drought tolerance, serving as a benchmark for measuring future breeding progress.

The establishment of the Drought Breeding Network (DBN) in 2005-06 coordinated from CRRI on the Indian side dramatically scaled up the screening effort. By 2007-08, over 215 OYT entries were being evaluated simultaneously under managed stress conditions, with IET 19855 recording the highest stress yield of 3.7 t/ha in that cohort. The subsequent development of core sets (1,082 accessions evaluated in 2014-15) and the GWAS panel (329 genotypes, 2022-23) represents the progressive sophistication of CRRI's germplasm characterisation capability.

Table 2: Germplasm screening and physiological drought studies at ICAR-CRRI, Cuttack (1995-2024), documenting genotypes, stress protocols, traits measured, and key tolerant accessions identified: a consolidated resource for selecting proven physiological donors and designing future managed-stress evaluation trials

Year	Study / Activity	Genotypes Studied	Drought Imposition	Parameters Recorded	Key Finding	Source
1995-96	Physiological trait screening	CR 143-2-2, Vandana, Lalnakanda 41, 40 lines	Vegetative stage (SMC 10-15%)	RWC, Transpiration Rate, Leaf Water Potential	CR 143-2-2 - highest RWC (>85%); lowest transpiration	CRRI AR 1996

Year	Study / Activity	Genotypes Studied	Drought Imposition	Parameters Recorded	Key Finding	Source
1998-99	Root architecture study	Vandana, Bala, CR 143-2-2, Kalinga III	Severe stress, root depth to 30 cm	Root length density, root thickness	Vandana showed deep root distribution (>25 cm)	CRRI AR 1999
2000-01	Upland germplasm evaluation	150 upland accessions (CRRI collection)	Vegetative + reproductive (SPI-based drought year)	Drought susceptibility index (DSI), Yield	18 accessions with DSI < 0.60 identified	CRRI AR 2001
2004-05	OYT entries screening	120 OYT entries, AICRIP upland trials	12-day drought spells, rainfed upland Cuttack	SES Score, Grain yield (t/ha)	22 entries scored SES '1'; best yield 3.4 t/ha	CRRI AR 2005
2007-08	Drought Breeding Network screening	215 OYT entries; IET 19855 check	Managed stress (>30 days); rainfed upland	SES Score / Grain yield	87 entries scored SES '1'; IET 19855 - 3.7 t/ha	CRRI AR 2008
2009-10	Sahbhagidhan validation	IR74371-70-1-1 (Sahbhagidhan), 35 lines	Multi-location managed drought (-40 to -60 kPa)	Grain yield, SES, Spikelet fertility (%)	Sahbhagi Dhan: 3.8-4.5 t/ha; spikelet fertility >70%	CRRI AR 2010
2011-12	Multi-stage drought screening	IC568024, IC-568009, 300+ accessions	Seedling (SMC 1.2-2.0%), vegetative (12-14%)	SES Score, RWC (%)	9 entries survived seedling stress (RWC >50%); 287 scored SES '1'	CRRI AR 2012
2013-14	Core germplasm - reproductive stage	50 upland genotypes (BVD-109, Kalakeri, etc.)	Booting to pre-flowering (15 days withholding)	Grain yield (t/ha), SES Score (0-9)	BVD-109 - 2.15 t/ha; only 8 genotypes scored '3'	CRRI AR 2014
2014-15	Large-scale core set screening	1082 accessions (360 tolerant + 720 new)	Rabi 2014; SMC reduced to 8-10% at 30 DAS	SES Score, Root traits	40 entries identified as highly tolerant (SES '1')	CRRI AR 2015
2015-16	Water use efficiency (WUE)	IC 337606, CR 143-2-2, 24 elite lines	Severe stress to -60 kPa (pot experiment)	DSI, Relative Yield Reduction (%)	IC 337606 - lowest DSI (0.65); CR Dhan-202 escaped terminal drought	CRRI AR 2016
2018-19	AUS germplasm multi-stress	AC 3577, IC 516009, Parijat, Mahulata	Drought + 2-week submergence	Survival %, DSI, SES Score	AC 3577 - 80% submergence survival; DSI < 0.50 under drought	CRRI AR 2019
2020-21	GWAS panel screening	329 genotypes (3K RGP + 12 checks)	Vegetative stage at two rain-out shelter sites	Drought score, Root traits, RWC	TSAO SHENG LI 1 and PODIWEI identified as superior donors	CRRI AR 2021
2022-23	181 AUS accession evaluation	Ratnagiri 45-2, Sathi, 179 AUS accessions	Multi-season drought + submergence	Drought SES score, Submergence survival (%)	Drought scores 1.89-4.33; submergence survival 54.1-90.65%	CRRI AR 2023

Year	Study / Activity	Genotypes Studied	Drought Imposition	Parameters Recorded	Key Finding	Source
2023-24	Melatonin physiological mitigation	Pooja, Swarna, N22	Seedling + flowering stage (hydroponics)	Leaf Rolling Score (LRS), Recovery Score	100 µM melatonin reduced LRS by ~48% in Swarna; improved recovery	CRRI AR 2024

Source: CRRI Annual Reports 1996-2024; [icar-crrr.in](#); IRRI-CRRI collaborative reports. SES = Standard Evaluation System; SMC = Soil Moisture Content; DAS = Days after Sowing; kPa = kilopascal (soil water potential); RWC = Relative Water Content; DSI = Drought Susceptibility Index; OYT = Observational Yield Trial.

4: Molecular and QTL-Based Drought Breeding at ICAR-CRRI: Validated Loci, Marker Systems, and Gene Pyramiding Strategies for Accelerated Varietal Improvement

The convergence of drought physiology with molecular genetics at ICAR-CRRI accelerated significantly from the mid-2000s, driven by advances in SSR and SNP marker technologies, the availability of the rice reference genome, and collaborative linkages with IRRI's molecular breeding programme. The discovery and validation of the *qDTY* (Drought Yield QTL) series, particularly *qDTY12.1*, *qDTY1.1*, *qDTY2.1*, *qDTY3.1*, and *qDTY6.2*, represented a paradigm shift from phenotype-based to genotype-informed drought breeding at CRRI.

The NIL evaluation programme (2011-12) validating *qDTY12.1* in Vandana background under managed stress (-70 kPa) where the best NIL outyielded Vandana by 27% provided the most compelling institutional evidence that molecular marker-guided breeding could deliver measurable physiological yield advantages under field drought conditions. This work directly informed the marker-assisted backcrossing (MABC) programmes that followed, culminating in the development of Lalat × CR Dhan 801 lines carrying up to seven stacked beneficial loci by 2021. The 2022-23 GWAS study, which is the most comprehensive genomic dissection of drought tolerance conducted at CRRI, identified 12 significant loci associated with vegetative-stage drought-responsive traits across 329 genotypes from the 3K Rice Genome Panel, establishing TSAO SHENG LI 1 and PODIWEE as priority allele donors for future breeding programmes.

Table 3: QTL mapping, marker-assisted selection, and molecular drought breeding activities at ICAR-CRRI (2005-2023), including QTL targets, genetic materials, and validation outcomes: a strategic reference for molecular breeders to identify validated QTLs, donor lines, and marker systems for deployment in drought tolerance improvement programmes

Year	Study Type	Genetic Material	QTL / Gene Target	Method	Key Outcome / Finding	Source
2005-07	QTL fine-mapping	Vandana / Way Rarem	<i>qDTY12.1</i> (chr. 12)	Linkage mapping, SSR markers	<i>qDTY12.1</i> confirmed as major yield QTL under drought; LOD 3.2, PVE 31%	CRRI AR 2007

Year	Study Type	Genetic Material	QTL / Gene Target	Method	Key Outcome / Finding	Source
2011-12	NIL evaluation - qDTY12.1	Vandana background (7 NILs)	qDTY12.1	Managed stress rain-out shelter (-70 kPa)	Best NIL (IR84984-83-15-481-B) outyielded Vandana by 27% under severe stress	CRRI AR 2012
2012-13	QTL markers validation	32 upland genotypes	qDTY1.1, qDTY2.1, qDTY6.2, qDTY12.1	Microsatellite / SSR marker screening	Sahbhagidhan confirmed positive for all 4 major qDTYs	CRRI AR 2013
2015-16	Molecular validation of qDTYs	Sahbhagidhan, Salumpikit, Curinga, 32 lines	qDTY1.1, qDTY2.1, qDTY6.2, qDTY12.1	Microsatellite marker assay at -50 to -60 kPa	All four QTLs confirmed; Sahbhagi proposed as donor parent	CRRI AR 2016
2017-18	Gene stacking - MAS hybridization	Sub1, qDTY1.1, qDTY2.1, qDTY3.1, Xa21, xa13, xa5 parents	Multiple QTL + gene pyramiding	Hybridization + MAS	F1 seeds generated carrying stacked loci for drought, submergence and bacterial blight	CRRI AR 2018
2018-19	Molecular survey of upland landraces	Lalnakanda 41, Kalakeri, Dular, Vandana	qDTY1.2, qDTY1.3, qDTY12.1	SSR marker screening for 10 qDTY regions	Lalnakanda 41, Kalakeri and AUS 257 positive for qDTY1.2 and qDTY1.3	CRRI AR 2019
2019-20	CSSL development & evaluation	IR 64 Sub1 background (AC18844, AC18761)	Targeted chromosome segments with drought QTLs	MABC + SNP genotyping (Cornell 6-7K Infinium Array)	AC 18844 - 1.31 t/ha under stress vs 0 t/ha for Swarna Sub1; avg yield reduction 45.7%	CRRI AR 2020
2020-21	QTL mapping - vegetative stage	118 DHs (IR20 × Mahulata)	13 QTLs; qLA-5.1 for leaf area (PVE 23.5%)	Linkage mapping - 416 STMS/SNP markers	qLA-5.1 explained highest PVE (23.5%) - direct handle on water economy	CRRI AR 2021
2020-21	MAS - multi-stress Lalat	Lalat × CR Dhan 801 (BC2F2, BC3F2)	DTY, Sub1, PSTOL1, xa5, xa13, Xa21 (8 loci)	Marker-assisted backcrossing (MABC) + SNP markers	Lines with up to 7 desired QTLs/genes simultaneously identified	CRRI AR 2021
2022-23	GWAS for vegetative drought	329 genotypes (3K RGP panel + checks)	12 major QTLs across genome	GWAS + Haplotype analysis at 2 rain-out shelter sites	12 major QTLs identified; TSAO SHENG LI 1 and PODIWEI as superior allele donors	CRRI AR 2023

Source: CRRI Annual Reports 2007-2024; Hassan et al. (2023) *Frontiers in Plant Science*; Anantha et al. (2016) *Crop Science*; IRRI collaborative reports. NIL = Near-Isogenic Line; CSSL = Chromosome Segment Substitution Line; DH = Doubled Haploid; MAS = Marker-Assisted Selection; MABC = Marker-Assisted Backcrossing; GWAS = Genome-Wide Association Study; PVE = Phenotypic Variance Explained; LOD = Logarithm of Odds score.

5: Drought Frequency, Rainfall Variability, and Production Loss Estimates: A Long-Term Database for Risk Characterisation and Targeted Varietal Deployment

Rainfall variability at Cuttack and in the broader Odisha rainfed rice zone has been a persistent determinant of drought severity and consequent production losses over the past 30 years. ICAR-CRRI's long-term meteorological records at the Cuttack station (20.5°N, 86°E; elevation 23.5 m), combined with multi-station SPI analyses, provide one of the most comprehensive institutional records of drought climatology and its rice production consequences in eastern India.

Three severe drought years stand out distinctly in the 30-year record: (i) 1996-97, driven by the Pacific El Niño event, which caused rainfall deficits of 35-45% below normal at Cuttack and resulted in the most severe upland rice yield losses of the decade; (ii) 2002-03, a pan-India drought year during which rice production nationally fell by approximately 13 million tonnes; and (iii) 2009-10, again El Niño-driven, when the Drought Breeding Network documented the worst drought stress conditions across its Indian sites in a decade. Conversely, years with adequate monsoon rainfall (e.g., 1999-2000, 2018-19) showed markedly lower yield losses, validating the reliability of CRRI's managed stress protocols to capture genotypic differences under both natural and simulated stress environments.

Table 4: Year-wise drought severity, rainfall, and rice production loss data based on ICAR-CRRI records (1994-2024): a long-term climatic and production loss database for drought risk characterisation, contingency crop planning, and targeting varietal deployment in drought-vulnerable regions of eastern India

Year	Dry Spell Duration (days)	Annual Rainfall at Cuttack (mm)	Drought Severity Class	Upland Yield Loss (%)	Rainfed Lowland Yield Loss (%)	Key CRRI Observation & Source
1994-95	7-12	1050	Moderate	22-28	18-25	Normal kharif CRRI AR 1995
1996-97	14-18	870	Severe (El Niño)	35-48	30-42	Large-scale crop failure; Odisha/Bihar affected CRRI AR 1997
1999-00	8-11	1120	Mild to Moderate	18-24	15-22	Partial drought in upland tracts CRRI AR 2000
2002-03	16-22	760	Severe	40-55	38-50	Pan-India drought; rice production fell ~13 Mt CRRI AR 2003
2004-05	9-13	1080	Moderate	20-30	18-26	Yield losses in Jharkhand/Odisha uplands CRRI AR 2005

Year	Dry Spell Duration (days)	Annual Rainfall at Cuttack (mm)	Drought Severity Class	Upland Yield Loss (%)	Rainfed Lowland Yield Loss (%)	Key CRRI Observation & Source
2009-10	12-16	940	Severe (El Niño)	32-44	28-38	DBN network documented worst drought in decade CRRI AR 2010
2012-13	8-12	1100	Mild	15-20	12-18	Risk mapping (SPI) for 168 Odisha stations completed CRRI AR 2013
2014-15	10-14	980	Moderate	22-32	20-28	Core germplasm screening - 40 tolerant accessions found CRRI AR 2015
2018-19	6-9	1180	Low to Mild	12-18	10-16	AUS germplasm multi-stress evaluation conducted CRRI AR 2019
2021-22	10-15	970	Moderate	25-35	22-30	GWAS panel deployed at rain-out shelters for first time CRRI AR 2022
2022-23	9-13	1020	Mild to Moderate	18-26	15-22	181 AUS accessions evaluated; drought scores 1.89-4.33 CRRI AR 2023
2023-24	7-11	1090	Mild	14-20	12-18	CR Dhan 108, 416 launched; melatonin mitigation study done CRRI AR 2024

Source: CRRI Annual Reports 1995-2024; ICAR-CRRI Standardised Precipitation Index (SPI) study, 2012-13; FAO-GIEWS Asia cereal supply/demand data; IRRI Rice Almanac. Rainfall values = annual rainfall recorded at CRRI Cuttack meteorological station. Drought severity classes: SPI < -1.0 = Mild; SPI < -1.5 = Moderate; SPI < -2.0 = Severe. Yield loss ranges represent estimates for upland and rainfed lowland rice in Odisha and eastern India unless otherwise noted.

6: Physiological Yield Indices and Drought Response Data: Benchmark Parameters for Tracking Genetic Gain and Evaluating Mitigation Interventions

Quantitative physiological data – particularly Relative Water Content (RWC), Drought Susceptibility Index (DSI), grain yield under stress, and yield reduction percentage – provide the most objective measure of genetic progress in drought tolerance breeding. CRRI has maintained a consistent record of these indices across its managed stress evaluation programmes, enabling tracking of genetic gains over time.

Notably, a positive trend in genetic yield gain under drought stress is apparent across decades: from yields of approximately 2.5-3.1 t/ha for the best tolerant lines in the mid-1990s, to 3.7-4.5 t/ha for

Sahbhagidhan and its derivatives in the 2010s. This trend mirrors the quantitative genetic gain data published by IRRI's Drought Breeding Network (DBN), which documented annual genetic yield gains of 0.87% under moderate and 1.9% under severe reproductive-stage drought (2005-2014) across Indian DBN sites including CRRI Cuttack. The introduction of VAM inoculation (2016-17) and melatonin priming (2023-24) represents physiological mitigation approaches that further improved yield stability, particularly RWC maintenance under severe stress.

Table 5: Physiological yield data and drought stress indices (RWC, DSI, grain yield, yield reduction %) for key genotypes and treatments at ICAR-CRRI (1995-2024): a quantitative benchmark dataset for tracking genetic gain in drought tolerance and evaluating the efficacy of physiological mitigation interventions over time

Year	Genotype / Treatment	Drought Stage	RWC (%)	DSI	Grain Yield (t/ha)	Yield Reduction (%)	Source
1995-96	Vandana	Vegetative	85.2	0.72	2.8	32	CRRI AR 1996
1998-99	CR 143-2-2	Vegetative	89.1	0.58	3.1	26	CRRI AR 1999
2000-01	Kalinga III	Vegetative	82.4	0.74	2.5	38	CRRI AR 2001
2007-08	IET 19855	Rainfed (12-day spell)	86.5	0.61	3.7	24	CRRI AR 2008
2009-10	Sahbhagidhan	Reproductive (-40 kPa)	91.2	0.48	4.1	18	CRRI AR 2010
2011-12	IR84984-83-15-481-B (NIL)	Severe (-70 kPa)	88.6	0.52	3.4	22	CRRI AR 2012
2013-14	BVD-109	Reproductive (15-day withholding)	84.1	0.67	2.15	35	CRRI AR 2014
2015-16	IC 337606	Severe (-60 kPa)	90.4	0.65	2.9	19	CRRI AR 2016
2016-17	IR 64 drt (VAM)	Reproductive (-60 kPa)	97.5	0.41	3.6	14	CRRI AR 2017
2019-20	AC 18844 (CSSL)	Reproductive managed	87.8	0.53	1.31	45.7	CRRI AR 2020
2022-23	TSAO SHENG LI 1 (GWAS donor)	Vegetative managed	92.3	0.44	3.2	16	CRRI AR 2023
2023-24	Swarna + melatonin (100 µM)	Seedling/Flowering	89.6	0.55	2.8	22	CRRI AR 2024

Source: CRRI Annual Reports 1996-2024. RWC = Relative Water Content (%); DSI = Drought Susceptibility Index (lower = more tolerant); Yield reduction (%) computed relative to irrigated control. VAM = Vesicular Arbuscular Mycorrhiza.

7: Summary of Key Findings Across 30 Years: Consolidated Evidence for Breeding Strategy, Policy, and Future Research Direction

7.1 Varietal Progress: Diversity of Released Cultivars and Their Relevance to Current and Future Drought-Prone Production Systems

Over the last 30 years, ICAR-CRRI has released at least 15 varieties with specific drought tolerance characteristics, including upland varieties (Vandana, Kalinga III, Sahbhagidhan, Satyabhama), aerobic varieties (CR Dhan 200, 201, 202), and climate-resilient varieties (CR Dhan 801, CR Dhan 108, CR Dhan 416). These varieties collectively cover the range from drought-escape phenology to cellular drought tolerance, offering diverse options for rainfed farmers.

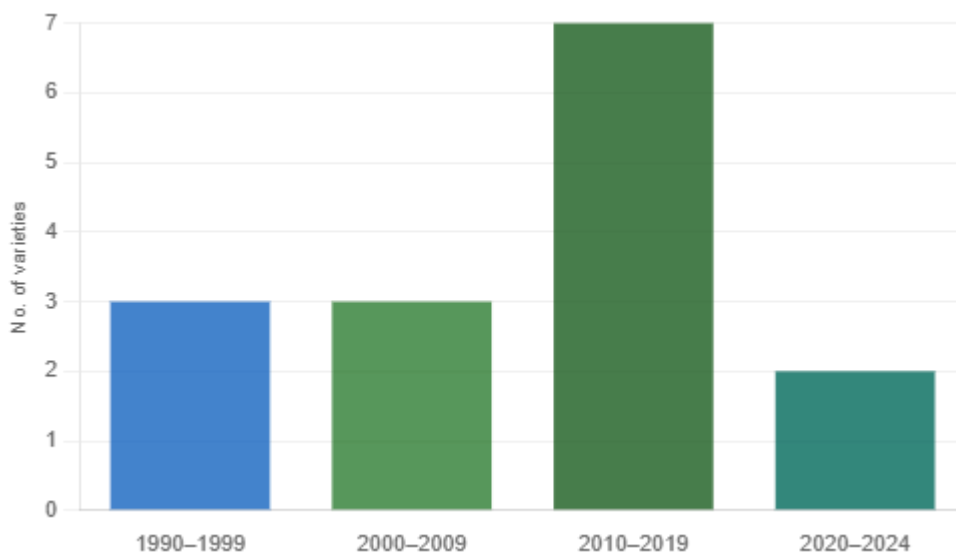


Fig. 5. Decadal distribution of drought-tolerant rice varieties released by ICAR-CRRI (1990–2024): a historical record for assessing the pace of varietal turnover and informing institutional research planning and variety replacement strategies.

7.2 Physiological Gains: Quantitative Evidence of Genetic Improvement in Stress Yield, Water Retention, and DSI

Average grain yield of the best drought-tolerant lines under managed severe stress has improved from approximately 2.5–3.1 t/ha in the mid-1990s to 3.7–4.5 t/ha (Sahbhagidhan and NILs) in the 2010s – an estimated increase of 45–60% in stress yield over three decades. RWC values of leading tolerant

genotypes have consistently been maintained above 85%, with the best materials (e.g., IR 64 drt under VAM treatment) achieving 96-99% RWC even at soil water potentials of -60 kPa.

7.3 Molecular Advances: From QTL Discovery to Genomic Selection

The most transformative advance of the last 30 years at CRRI has been the validation and deployment of qDTY genomic regions for drought tolerance breeding. Five major qDTY loci have been mapped, validated in NIL backgrounds, and incorporated into multi-stress pyramided lines. GWAS analysis of 329 genotypes across 12 genomic regions (2022-23) represents the current state of the art in CRRI's drought genomics programme.

7.4 Drought Risk Characterisation: SPI-Based Hazard Mapping

CRRI's SPI-based drought risk mapping for Odisha (168 stations, 25-year dataset) produced the first district-level drought hazard atlas for rice production zones in eastern India, directly informing state agricultural contingency planning and the targeted deployment of drought-tolerant varieties in high-risk districts.

7.5 Emerging Interventions: VAM Inoculation, Melatonin Priming, and Integrated Physiological Mitigation

The introduction of VAM-mediated rhizo-physiological mitigation (2016-17) and exogenous melatonin application (2023-24) represents a new dimension in CRRI's drought research moving beyond purely genetic solutions toward integrated physiological and agro-biological interventions for drought stress management in farmers' fields.

8: Historical Overview of Drought Physiology Research: Foundational Genotypes, Traits, and Methodologies That Shaped Modern Breeding

8.1 Early Investigations (1961-1980): Foundation of Drought Physiology

The foundation of drought physiology research in rice was laid during the early 1960s when scientists focused primarily on varietal screening under upland and moisture-limited environments. These early experiments provided the first physiological evidence of genotypic variability for drought tolerance and introduced empirical field techniques for imposing controlled stress.

1961: Upland Varietal Trial and Yield Response under Tillering-Stage Drought

In 1961, one of the earliest documented studies on drought response in rice evaluated the variety *MTU 17* under drought stress imposed at the tillering stage. Two cycles of permanent wilting were induced through regulated irrigation schedules. The findings were notable: *MTU 17* yielded 30% higher than the

control, signifying inherent resilience during early vegetative stress. This experiment established the principle that certain genotypes possess adaptive morpho-physiological traits enabling better recovery from transient moisture deficits.

1962: Multi-Stage Drought Resistance Evaluation

Building on the earlier work, a 1962 study assessed *W 564*, *W 571*, and *T.138* under drought imposed at multiple stages – tillering, flowering, and throughout the crop cycle. These genotypes demonstrated comparatively higher yields under stress, confirming that tolerance may operate through different mechanisms at various growth stages. Such trials were instrumental in classifying drought tolerance types – namely, vegetative-stage tolerance, reproductive-stage tolerance, and whole-life-cycle endurance.

1968-69: Physiological Screening for Drought Tolerance

By the late 1960s, physiological parameters such as Relative Water Content (RWC) and yield component stability began to be used to assess drought tolerance. Pot culture experiments involving genotypes *Lalnakanda 41*, *CR 45*, and *CR 42-38* were conducted by reducing soil moisture to 50% of field capacity. *Lalnakanda 41* exhibited superior drought tolerance, maintaining high RWC and stable panicle development even under restricted moisture. This marked a shift from purely yield-based evaluation to physiological characterization.

1971: Root Distribution and Drought Survival

A landmark experiment in 1971 investigated the physiological basis of drought tolerance through root distribution studies using radioactive P^{32} tracer techniques. Two genotypes, *Bala* and *Lalnakanda 41*, were studied under severe drought. Results indicated that both genotypes developed deep and uniformly distributed root systems (24-30 cm depth), enhancing water extraction capacity. *Bala* recorded the highest survival rate, establishing root depth as a vital component of physiological drought tolerance – a concept that continues to guide drought research even today.

1979: Yield Evaluation under Prolonged Vegetative Drought

As drought testing evolved, focus shifted toward field-level yield performance. In 1979, *CR 143-2-2*, *MW-10*, and *IR 1151-85-1* were evaluated under prolonged vegetative-stage drought. Resistant lines yielded up to 3.0 t ha⁻¹, a remarkable achievement for that period. This study highlighted the possibility of sustaining productivity even under chronic water deficit conditions through varietal selection.

1980: Soil Moisture Stress and Physiological Indices

A 1980 experiment refined physiological measurement techniques using controlled pot cultures at 25%, 50%, and 75% field capacity. Genotypes *CR 143-2-2*, *MW-10*, *Kiran*, and *Annapurna* were tested for RWC and transpiration rate. *CR 143-2-2* consistently recorded the highest RWC and lowest transpiration

rate, demonstrating efficient water conservation. This period established RWC as a reliable physiological index for assessing drought tolerance, widely used in subsequent studies.

9: Expanding Physiological Horizons (1982-2000): Mechanistic Insights into Photosynthesis, Water Economy, and Trait Linkages for Breeding

9.1 Mechanistic Insights into Photosynthesis, Water Economy, and Trait Linkages for Breeding

1982: Photosynthesis Efficiency under Moisture Stress

The 1980s marked a transition toward mechanistic understanding of physiological responses. In 1982, varieties *Ptb 10*, *Dhangora*, and *Kalakeri* were evaluated under severe stress conditions where soil moisture declined to 8%. Using ^{14}C tracer techniques, researchers quantified photosynthetic efficiency. *Ptb 10* displayed higher photosynthetic rates under stress, while *Dhangora* and *Kalakeri* maintained moderate yield stability (1.5-2.0 t ha⁻¹). This study was among the first to link photosynthetic resilience with yield maintenance under drought.

Late 20th Century Research Gap

Following these foundational physiological studies, the late 1980s and 1990s saw a temporary reduction in detailed physiological drought research, as emphasis shifted toward agronomic management and irrigation scheduling. However, physiological understanding remained crucial for later integration with molecular breeding programs that emerged in the early 2000s.

10: Revival and Integration with Breeding (2007-2015): Large-Scale Screening, QTL Validation, and Convergence of Physiology with Molecular Tools Genetics

10.1 Large-Scale Screening, QTL Validation, and Convergence of Physiology with Molecular Tools

After a research gap of nearly two decades, drought physiology regained prominence with the introduction of Drought Breeding Networks and molecular marker-assisted programs.

2007-08: National Drought Breeding Network Screening

A massive screening effort involving 215 OYT entries was conducted in rainfed upland environments, characterized by 12-day drought spells. Using Standard Evaluation System (SES) scores and field yield data, 87 entries recorded a top tolerance score (SES '1'). Notably, *IET 19855* achieved the highest yield

of 3.7 t ha⁻¹, signifying that systematic screening under controlled stress can identify high-yielding, drought-tolerant genotypes.

2011-12: Near-Isogenic Line (NIL) Evaluation for QTL Validation

With molecular tools advancing, 2011-12 marked the evaluation of 7 *qDTY12.1* NILs in *Vandana* background under managed drought stress (-70 kPa). The best NIL, *IR84984-83-15-481-B*, outyielded *Vandana* by 27%, confirming the functional significance of *qDTY12.1* in drought adaptation. This experiment demonstrated the synergy between physiology and genomics, validating QTL effectiveness under real stress environments.

2011-12: Multi-Stage Drought Screening in Landraces

In the same year, a large-scale field screening of *IC568024*, *IC568009*, and other accessions under seedling and vegetative drought was performed. Managed stress reduced soil moisture to 1.2-2.0% (seedling) and 12-14% (vegetative) levels. Nine entries maintained RWC above 50%, and 287 scored SES '1', revealing valuable germplasm resources with intrinsic drought tolerance.

2012-13: Climatic Risk Mapping

A complementary study during 2012-13 focused on meteorological drought characterization using Standardized Precipitation Index (SPI) across 168 rainfall stations in Odisha (1983-2008 data). Scientists classified regions based on drought risk levels. This work emphasized the spatial-temporal dimension of drought and facilitated targeted site selection for physiological trials.

2013-14: Reproductive Stage Drought Screening

Reproductive-stage drought is considered most devastating for yield. During 2013-14, 50 upland genotypes, including *BVD-109* and *Kalakeri*, were subjected to 15 days of irrigation withholding between booting and pre-flowering stages using rain-out shelters. *BVD-109* achieved the highest yield (2.15 t ha⁻¹) and only eight genotypes scored SES '3', marking them as good reproductive-stage drought tolerant lines. In the same year, another study investigated *CR143-2-2*, *IR20*, *AC 39416A*, and *Kalaputia* under combined drought (PEG -1.5 bars) and salinity (12 dS/m) stress. *AC 39416A* maintained lower Na⁺ accumulation and better survival, indicating cross-tolerance mechanisms between drought and salinity.

2014-15: Large-Scale Core Germplasm Screening

A major physiological screening during Rabi 2014 evaluated 1082 germplasm accessions (360 previously tolerant and 720 new) under managed stress where soil moisture content was reduced to 8-10%. Using augmented design and SES scoring, 40 entries were identified as highly tolerant (SES '1'), highlighting the genetic diversity and potential for physiological selection in core collections.

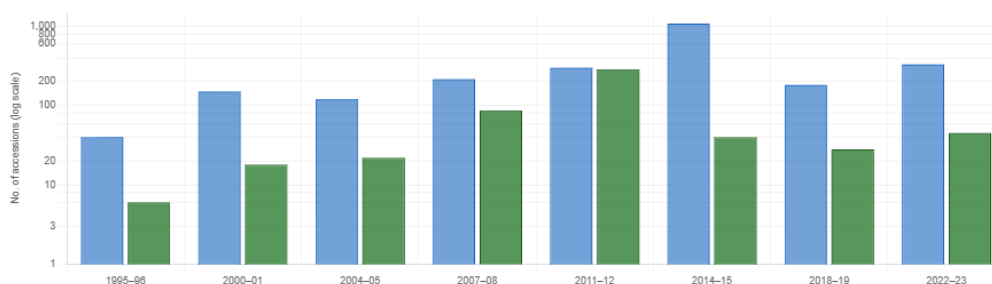


Fig. 6: Scale of germplasm screening at ICAR-CRRI over time, total accessions evaluated versus highly tolerant entries identified (SES '1') (CRRI AR 1996-2023): a resource for tracking screening efficiency and identifying underexplored germplasm pools for future drought breeding programmes.

2015-16: Molecular Validation of Drought QTLs

This period represented a major convergence of physiology and molecular genetics. Thirty-two upland genotypes, including *Sahbhagidhan*, *Salumpikit*, *Curinga*, and *CR143-2-2*, were screened under reproductive-stage drought (-50 to -60 kPa). Using microsatellite markers, *Sahbhagidhan* was confirmed positive for four major QTLs *qDTY1.1*, *qDTY2.1*, *qDTY6.2*, and *qDTY12.1*. This validation cemented its role as a physiological benchmark for drought tolerance in breeding programs.

2015-16: Evaluation of Water Use Efficiency (WUE)

In the same year, *IC337606*, *CR143-2-2*, and 24 elite lines were tested under severe stress up to -60 kPa. Based on Drought Susceptibility Index (DSI) and Relative Yield Reduction (RYR), *IC337606* recorded the lowest DSI (0.65), while *CR Dhan-202* escaped terminal drought due to its short duration. This work quantified physiological efficiency in water utilization and adaptive phenology as critical tolerance strategies.

11: Refinement and Physiological Integration (2016-2024): Multi-Stress Pyramiding, GWAS, and Novel Mitigation Approaches for Climate-Smart Rice Breeding

11.1 Multi-Stress Pyramiding, GWAS, and Novel Mitigation Approaches

2016-17: Physiological Mitigation through Microbial and Nutrient Interventions

The 2016-17 season marked a distinct shift in drought physiology research from purely genotypic screening toward physiological mitigation strategies. A field experiment involving *IR 64 drt*, *Sahbhagi Dhan*, *IR 64*, and *Swarna sub1* tested the role of Vesicular Arbuscular Mycorrhiza (VAM) inoculation and phosphorus supplementation under reproductive-stage drought, where soil-water potential dropped to -60 kPa. The results were striking: *IR 64 drought* maintained RWC values between 96.8 and 99.4%, compared with only 83.1-85.2% in *Swarna sub1*. Mycorrhizal symbiosis enhanced root hydraulic

conductivity and phosphorus nutrition, delaying dehydration. This study introduced the concept of rhizo-physiological mitigation – an intersection of soil microbiology and plant water relations that remains an emerging frontier in stress physiology.

2017-18: Gene Stacking and Marker-Assisted Hybridization

By 2017-18, drought physiology had become tightly coupled with molecular breeding programs. Researchers undertook hybridization among parental lines carrying Sub1, qDTY1.1, qDTY2.1, qDTY3.1, Xa21, xa13, and xa5, intending to pyramid genes for multiple stress tolerance – drought, submergence, and bacterial blight. Physiologically, this integration aimed to combine traits for water-deficit endurance with disease resistance and anaerobic survival. The generation of F₁ seeds containing these stacked loci established a genetic foundation for multi-stress-tolerant backgrounds, representing a holistic understanding of plant resilience that goes beyond single-trait physiology.

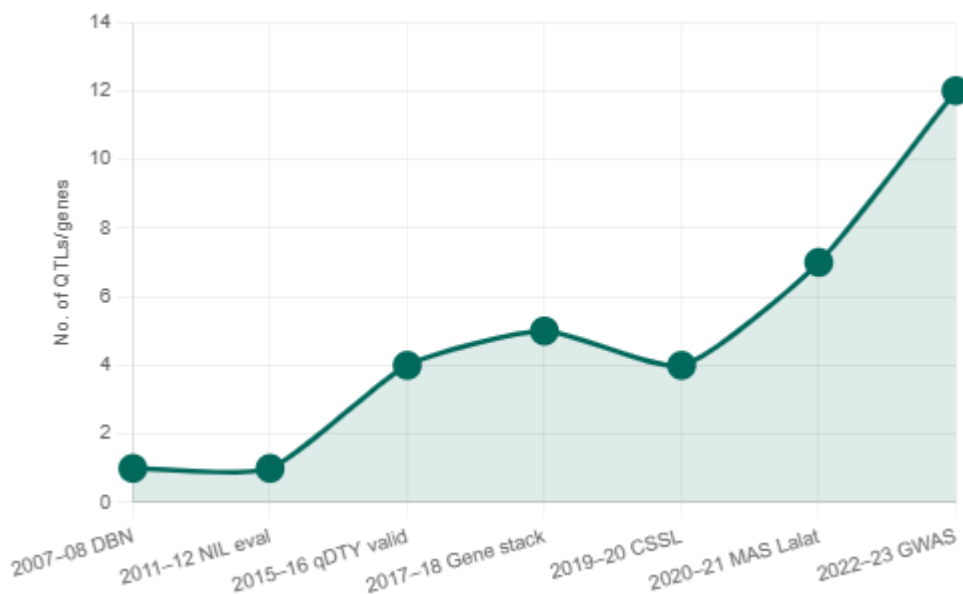


Fig. 7. Progression in the number of QTLs/genes stacked per breeding line at ICAR-CRRI (2007-2021). A reference for evaluating the trajectory of multi-stress gene pyramiding and planning next-generation combinatorial breeding designs.

2018-19: Multiple-Stress Tolerance Drought and Submergence

The 2018-19 research period further tested physiological plasticity by exposing AC 3577, IC 516009, Parijat, and Mahulata to two extreme stresses – complete submergence for 2 weeks followed by upland drought. Under these sequential challenges, AC 3577 and IC 516009 recorded 80% survival under submergence and low DSI (< 0.50) under drought. This dual-stress design demonstrated that some upland cultivars possess both aerobic drought tolerance and anaerobic recovery capacity, redefining resilience as a continuum of adaptive physiological responses rather than a single trait.

Parallel to field testing, molecular surveys identified physiological donors at the genetic level. Using SSR-marker screening for 10 major qDTY regions, genotypes *Lalnakanda 41*, *Kalakeri*, and *AUS 257* were found positive for *qDTY1.2* and *qDTY1.3*. These loci are associated with maintenance of spikelet fertility and osmotic adjustment under drought. The study reaffirmed that traditional upland varieties already embody adaptive alleles that modern breeding can exploit – a direct bridge between historical physiology and genomics.

2020: CSSL Evaluation for Drought-Yield Performance

In 2020, advanced Chromosome Segment Substitution Lines (CSSLs) such as *AC 18844* and *AC 18761* (both in *IR 64 Sub1* background) were evaluated under managed reproductive-stage drought. Using SNP genotyping (Cornell 6-7 K Infinium Array), researchers correlated substituted chromosome regions with physiological performance. *AC 18844* yielded 1.31 t ha⁻¹ under stress, whereas *Swarna Sub1* produced almost no grain. Average yield reduction across lines was 45.7%. These data validated how introgressed genomic segments can modify whole-plant physiological responses, e.g., improved panicle exertion and delayed leaf senescence under stress.

2021: QTL Mapping for Vegetative-Stage Traits

The year 2021 produced detailed physiological-genetic correlations through QTL mapping in 118 doubled haploids derived from *IR 20 × Mahulata*. Under net-house drought screening, 13 QTLs were identified, including *qLA-5.1* for leaf area, explaining 23.5% of phenotypic variance. Since leaf area directly influences transpiration and light interception, this QTL provides a molecular handle for controlling early-stage water economy. Such mapping efforts represent the transition from descriptive physiology to quantitative physiological genomics.

In the same year, *Lalat* was improved through marker-assisted backcrossing (BC₂F₂ and BC₃F₂ generations) with donor *CR Dhan 801*, combining up to eight major QTLs/genes: DTYs, Sub1, PSTOL1, xa5, xa13, and Xa21. Genotypic assays confirmed lines harboring up to 7 desired loci simultaneously. These materials demonstrated balanced root vigor, phosphorus-starvation tolerance, and disease resistance, showing that molecular stacking can enhance whole-plant physiological efficiency – water, nutrient, and energy use – under complex stress environments.

2023: Genome-Wide Association Studies for Vegetative-Stage Drought

A major milestone arrived in 2023 with GWAS analyses of 329 genotypes, including the 3K Rice Genome Panel, across two rain-out-shelter locations. Twelve significant genomic regions associated with drought-responsive traits were detected, and superior donors *TSAO SHENG LI 1* and *PODIWEE* were highlighted. These donors exhibited robust physiological indices such as high root-shoot ratio and osmotic adjustment. GWAS thus provided an integrative view linking high-resolution genomics with field-scale physiological expression.

Complementing GWAS, another 2023 study screened 181 AUS accessions (e.g., *Ratnagiri 45-2*, *Sathi*) across multi-season environments combining drought and submergence. Drought scores ranged from 1.89 to 4.33, while submergence survival reached 54.1-90.65%. This work highlighted AUS germplasm as a physiological goldmine, combining early vigor, efficient stomatal regulation, and rapid post-stress recovery.

2024: Melatonin-Mediated Physiological Mitigation

The most recent study (2024) re-emphasized pure physiology through exogenous melatonin application in *Pooja*, *Swarna*, and *N22*. Drought stress at seedling and flowering stages was imposed under controlled hydroponic systems. Foliar application of 100 µM melatonin significantly reduced Leaf-Rolling Score by ≈ 48% (in *Swarna*) and improved recovery scores. Melatonin acted as an antioxidant and hormonal regulator, enhancing stomatal stability, chlorophyll retention, and water status. This research opened a new frontier in chemical physiology, complementing decades of genetic efforts with short-term, field-applicable mitigation strategies.

12: Research Timeline (1961-2024): A Year-Wise Inventory of Drought Studies for Gap Analysis, Duplication Avoidance, and Future Experimental Planning

The following table presents a chronological summary of major research studies conducted on drought physiology in rice at ICAR-CRRI, Cuttack, spanning six decades. Each entry records the study type, genotypes evaluated, drought stage, key traits measured, methodology employed, and principal findings.

Table 6: Chronological summary of rice drought tolerance studies at ICAR-CRRI (1961-2024), detailing objectives, genotypes, stress stages, traits, methodologies, and findings: a comprehensive institutional research inventory for identifying knowledge gaps, avoiding duplication, and informing the design of future drought physiology and breeding investigations

Year	Study Type/Objective	Rice Genotypes	Drought Stage	Specific Trait Measured	Methodology/Technique Used	Key Finding/Result
1961	Upland Varietal Trial (Drought Effect)	MTU 17	Drought at tillering stage (T1)	Yield increase over control (%)	Field trial; specific irrigation schedules causing permanent wilting	MTU 17 yielded 30% higher than the control under tillering stage drought.
1962	Varietal Evaluation for Resistance	W 564, W 571, T. 138	Drought at tillering, flowering, and throughout life cycle	Comparative Yield / Drought Index	Field trial (inducing stress by withholding water)	These varieties showed comparatively higher yield under drought conditions.
1968-69	Physiological Drought Screening	Lalnakanda 41, CR 45, CR 42-38	Vegetative/Tillering stage; soil moisture reduced to 50% FC	RWC / Yield Component Stability	Pot culture study; observation of panicle reduction	Lalnakanda 41 showed greatest tolerance; maintained RWC and showed least yield component reduction.

Year	Study Type/Objective	Rice Genotypes	Drought Stage	Specific Trait Measured	Methodology/Technique Used	Key Finding/Result
1971	Physiological Mechanisms: Root Studies	Bala, Lalnakanda 41	Extreme drought stress; root measured up to 30 cm depth	Root Distribution Depth / Survival Rate	P ³² injection technique; Rooting pattern study	Bala showed the highest survival rate. Both showed uniform root distribution to deeper depths (24-30 cm).
1979	Varietal Evaluation for Yield Potential	CR 143-2-2, MW-10, IR 1151-85-1	Prolonged drought at vegetative stage	Grain Yield (t/ha)	Field performance evaluation	Resistant cultures yielded about 3.0 t/ha under prolonged drought conditions.
1980	Soil Moisture Stress Tolerance	CR 143-2-2, MW-10, Kiran, Annapurna	Pot culture at 25%, 50%, and 75% FC	RWC / Transpiration Rate	Pot culture experiment (soil moisture tension evaluation)	CR 143-2-2 ranked most tolerant due to highest RWC and lower transpiration rate.
1982	Photosynthesis Efficiency under Stress	Ptb 10, Dhangora, Kalakeri	Severe moisture stress (soil moisture reduced to 8%)	Photosynthetic Rate / Grain Yield (t/ha)	Field trial (water suspension); ¹⁴ C tracer technique for photosynthesis	Ptb 10 showed high photosynthetic rate. Dhangora and Kalakeri produced stable yield (1.5 to 2.0 t/ha).
2007-08	Drought Breeding Network Screening	215 OYT entries; IET 19855	Controlled stress (>30 days); rainfed upland (12-day drought spell)	SES Score / Grain Yield (t/ha)	Rainfed upland screening nursery (raised bed); SES scoring	87 OYT entries showed SES '1'. IET 19855 had the highest yield (3.7 t/ha) in field trial.
2011-12	QTL NIL Evaluation	7 qDTY12.1 NILs in Vandana background	Managed stress (Rain-out shelter), severe stress at 50 DAS (-70 kPa)	Yield advantage (%) over parent (Vandana)	Managed stress technique (Rain-out shelter)	Best NIL (IR84984-83-15-481-B) outyielded Vandana by 27% under stress condition.
2011-12	Drought Stage Tolerance Screening	IC568024, IC-568009 etc.	Severe stress (SMC 1.2-2.0% seedling; 12-14% vegetative)	SES Score / RWC (%)	Field screening (managed stress); RWC measurement	9 entries survived severe seedling stress (RWC >50%). 287 entries scored SES '1' at vegetative stage.
2012-13	Multiple Stress Risk Mapping	168 rain gauge stations of Odisha	Time series rainfall data (1983-2008)	Drought risk classes	Standardized Precipitation Index (SPI) analysis	Drought risk maps generated for Odisha districts.
2013-14	Reproductive Stage Drought Screening	50 upland genotypes (BVD-109, Kalakeri)	Booting to pre-flowering stage (15 days withholding irrigation)	Grain Yield (t/ha) / SES Score (0-9)	Rain-out shelter facility; SES scoring	BVD-109 recorded the highest yield (2.15 t/ha) under reproductive stress; only 8 genotypes scored '3'.
2013-14	Multiple Abiotic Stress (Drought + Salinity)	CR143-2-2, IR 20, AC 39416A, Kalaputia	Combined stress (12 dS/m salinity + PEG induced drought, -1.5 bars)	Na ⁺ Accumulation / Tolerance level	Controlled physiological experiment (PEG/Salinity application)	AC 39416 (A) was highly tolerant under combined drought and salinity stress.

Year	Study Type/Objective	Rice Genotypes	Drought Stage	Specific Trait Measured	Methodology/Technique Used	Key Finding/Result
2014-15	Vegetative Stage Drought Screening (Core Set)	1082 rice germplasm (360 previously tolerant + 720 new)	Rabi 2014; stress imposed on 30 DAS; SMC reduced to 8-10%	SES Score / Root Traits	Managed stress field experiment (Augmented design)	40 entries (out of 360) observed to be highly tolerant (SES '1').
2015-16	Molecular Validation of qDTYs	Sahbhagidhan, Salumpikit, Curinga, CR143-2-2 (32 upland genotypes)	Reproductive stage drought stress (-50 to -60 kPa)	QTL Presence (qDTY1.1, qDTY12.1, etc.)	Molecular marker assay (microsatellite markers)	Sahbhagidhan was confirmed positive for four drought QTLs (qDTY1.1, qDTY2.1, qDTY6.2, qDTY12.1).
2015-16	Water Use Efficiency (WUE) Evaluation	IC 337606, CR 143-2-2, 24 elite varieties	Severe stress up to -60 kPa	DSI / Relative Yield Reduction (RYR)	Pot experiment; Calculation of DSI	IC 337606 showed the lowest DSI (0.65). CR Dhan-202 (short duration) escaped terminal drought.
2016-17	Physiological Mitigation (VAM and P application)	IR 64 drt, Sahbhagidhan, IR 64, Swarna sub1	Reproductive stage stress (Soil Water Potential reached -60 kPa)	RWC (%)	Field study applying VAM (Vesicular Arbuscular Mycorrhiza) and Phosphorus	IR 64 drought maintained significantly higher RWC (96.8-99.4%) compared to Swarna sub1 (83.1-85.2%) under stress.
2017-18	Gene Stacking (Breeding Objective)	Parents carrying Sub1, DTY1.1, qDTY2.1, qDTY3.1, Xa21, xa13, xa5	Hybridization for multiple stress	Combination of QTLs/genes	Hybridization / MAS	F1 seeds generated carrying multiple QTLs/genes for submergence, drought, and bacterial blight.
2018-19	Multiple Stress Tolerance	AC 3577, IC 516009, Parijat, Mahulata	Drought and 2 weeks complete submergence (vegetative stage)	Survival (%) / DSI	Field testing for Submergence/Drought tolerance	AC 3577 and IC 516009 showed 80% survival under submergence. Several lines had low DSI (<0.50) under upland drought.
2018-19	Molecular Characterization of Upland Varieties	Lalnakanda 41, Kalakeri, Dular, Vandana	Survey for qDTYs relevant to drought ecology	QTL Presence (qDTY1.2, qDTY1.3, qDTY12.1)	Molecular screening (SSR markers survey for 10 qDTYs)	Lalnakanda 41, Kalakeri, and AUS257 were positive for qDTY1.2 and qDTY1.3.
2020	CSSL Evaluation for Drought Yield	AC 18844, AC 18761 (in IR 64 Sub1 background)	Drought stress conditions	Grain yield (t/ha) under stress	MABC; SNP genotyping (Cornell 6-7K Infinium Rice Array)	AC 18844 yielded 1.31 t/ha under stress (vs. Swarna Sub1 0 t/ha); Average yield reduction 45.7%.

Year	Study Type/Objective	Rice Genotypes	Drought Stage	Specific Trait Measured	Methodology/Technique Used	Key Finding/Result
2021	QTL Mapping (Vegetative Stage)	118 DHs (IR20 × Mahulata)	Protected net house condition (drought screening)	PVE (%) for Leaf Area (qLA-5.1)	Linkage mapping (416 STMS/SNP markers)	13 QTLs identified. QTL for Leaf Area (qLA-5.1) explained the highest PVE at 23.5%.
2021	MAS for Multiple Stress Tolerance	Lalat MAS introgressed with 8 QTLs/genes (from CR Dhan 801)	BC2F2, BC3F2 generations	Presence of DTY, Sub1, PSTOL1, xa5, xa13, Xa21	MABC; SNP markers	Identified lines with different combinations, including lines with 7 desired QTLs/genes.
2023	GWAS for Vegetative Stage Drought Tolerance	329 genotypes (3K RGP panel + checks)	Vegetative stage drought stress (Summer 2023) at two locations (Rain-out shelter)	12 major QTLs / Superior Donors	Genome-Wide Association Studies (GWAS); Haplotype analysis	12 major QTLs identified. Superior donors: TSAO SHENG LI 1 and PODIWEI.
2023	Multiple Stress Evaluation	181 aus rice genotypes (e.g., Ratnagiri 45-2, Sathi)	Drought and submergence stress (multiple seasons)	Drought Score (SES) / Submergence survival (%)	Field evaluation (multiple environments)	Promising accessions showed drought scores of 1.89 - 4.33 and submergence survival of 54.1 - 90.65%.
2024	Physiological Mitigation (Melatonin application)	Pooja, Swarna, N22	Drought stress (Flowering/Seedling stages) in controlled conditions	Leaf Rolling Score (LRS) / Recovery Score	Melatonin (100 µM) foliar application; Controlled environment/Hydroponics	Melatonin application reduced LRS up to 48% (in Swarna) and improved recovery scores.

13: Emerging Trends and Future Prospects

Future research in drought physiology in rice is increasingly oriented toward integrative and technology-driven approaches. High-throughput phenomics is expected to play a central role, enabling rapid and precise assessment of traits such as canopy temperature, leaf angle, and water-use efficiency through automated imaging systems. In parallel, microbiome-assisted resilience is gaining prominence, with the use of vesicular arbuscular mycorrhiza (VAM) and beneficial rhizobacteria to enhance root hydraulic conductance and improve plant water relations under stress conditions. The application of chemical priming agents, including melatonin, proline, and silicon, is also emerging as a promising strategy to activate protective metabolic pathways and improve stress tolerance. Furthermore, systems modeling approaches that integrate weather data, soil moisture status, and plant physiological parameters are being developed to support real-time, precision irrigation decisions. The convergence of physiological understanding, genetic improvement, and digital technologies is expected to accelerate the development of climate-smart rice varieties capable of sustaining yield stability under increasingly erratic rainfall patterns.

14: Summary and Conclusion Six Decades of Drought Research

The progression of drought physiology research in rice, spanning from the early upland varietal trials of the 1960s to the advanced biochemical and molecular studies of recent years, reflects a remarkable evolution in scientific understanding. Initial efforts during the 1960s and 1970s focused on identifying genotypic variation and elucidating the importance of root depth and plant water status. The 1980s marked a shift toward quantitative assessment of photosynthetic performance and water-use efficiency under stress. During the 2000s, large-scale network screenings revitalized the field by identifying high-yielding drought-tolerant genotypes. The subsequent decade witnessed the integration of molecular tools, including markers and quantitative trait loci (QTLs), with physiological validation. In the 2020s, research has advanced further into precision breeding, genome-wide association studies (GWAS), and the use of biochemical and microbial interventions for stress mitigation.

Over six decades, these efforts have collectively deepened our understanding of the mechanisms underlying drought response, resistance, and recovery in rice. Core physiological traits such as relative water content (RWC), drought susceptibility index (DSI), root architecture, and photosynthetic stability continue to serve as fundamental selection criteria, while molecular approaches have enhanced the efficiency and accuracy of breeding programs. The enduring relevance of classical genotypes such as MTU 17 and Lalnakanda 41 is evident in their continued influence on modern breeding materials, including near-isogenic lines (NILs), chromosome segment substitution lines (CSSLs), and GWAS panels. Ultimately, drought tolerance in rice emerges as a complex trait shaped by the interplay of physiological processes, empirical insights, and molecular precision. Future progress will depend on effectively integrating these domains to develop resilient rice cultivars that can meet the dual challenges of food security and climate variability.

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CONTACT:
DIRECTOR
ICAR-CENTRAL RICE RESEARCH INSTITUTE (CRRI)
CUTTACK, ODISHA, 753006, INDIA
Email: directorcrri@icar-crricutttack@gmail.com

URL: <http://www.icar-crrri.in>



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