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PHYSIOLOGICAL ADVANCES IN RICE RESEARCH AT ICAR-CRRI: ENHANCING YIELD, PHOTOSYNTHETIC EFFICIENCY, AND CLIMATE RESILIENCE FOR SUSTAINABLE PRODUCTIVITY

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Enhancing Yield, Photosynthetic Efficiency, and Climate
Resilience for Sustainable Productivity**

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Preface

Rice (*Oryza sativa* L.) continues to be central to food and nutritional security, particularly in countries like India where it sustains a large proportion of the population. Over the years, the challenge has not only been to increase production but to do so under constraints imposed by climate variability, declining resource availability, and evolving biotic and abiotic stresses. This research bulletin is an effort to compile and synthesize three decades of systematic research carried out at ICAR-Central Rice Research Institute (ICAR-CRRI), Cuttack, with a focus on understanding and improving rice productivity through physiological, agronomic, and molecular approaches.

The work presented in this bulletin is the outcome of extensive experimentation conducted between 2000 and 2024, covering diverse rice ecologies and management systems. A major emphasis has been placed on elucidating the physiological determinants of yield, including crop growth rate, net assimilation rate, leaf area index, and harvest index, and their interaction with environmental and management factors. In addition, detailed investigations into photosynthesis, nutrient use efficiency, and dry matter partitioning have provided deeper insights into the mechanisms driving yield enhancement.

Another important aspect of this compilation is the integration of physiology with breeding. The identification of key traits and their translation into breeding programs through conventional selection, marker-assisted approaches, and recent genome editing tools has significantly contributed to the development of high-yielding and climate-resilient rice varieties. Efforts towards improving tolerance to drought, submergence, and high temperature, along with advancements in direct-seeded rice and precision nutrient management, reflect the institute's commitment to sustainable and adaptive rice production systems.

This bulletin also highlights the importance of bridging research with field application. Farmer participatory trials and large-scale demonstrations have validated many of the technologies developed, ensuring their relevance and adoption under real farming conditions. Such integration of research, extension, and feedback has been instrumental in translating scientific findings into tangible productivity gains. The preparation of this bulletin has been a collaborative effort, drawing upon the contributions of numerous scientists, technical staff, and field personnel over the years. Their dedication and sustained efforts have made it possible to generate a comprehensive body of knowledge that not only documents past achievements but also provides direction for future research.

It is hoped that this bulletin will serve as a useful reference for researchers, students, and policymakers, and will contribute to ongoing efforts aimed at enhancing rice productivity in a sustainable and climate-resilient manner.

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1: Introduction to Rice Physiological Research at ICAR-CRRI and Its Significance for Enhancing Productivity and Climate Resilience

Rice (*Oryza sativa* L.) is the staple food for more than two-thirds of the Indian population. Approximately half of the rice-growing areas in India are rainfed ecologies, predominantly situated in the eastern regions of the country (Varma, 2017). The ICAR-Central Rice Research Institute (ICAR-CRRI), formerly known as the ICAR-National Rice Research Institute (ICAR-NRRI), has been developing new technologies to increase rice yield and productivity and enhance its profitability and sustainability. The main objective is to sustain and further enhance crop productivity to meet the increasing demands of a growing population, which is expected to reach 1.6 billion by 2050 (Nayak et al., 2019). The ICAR-CRRI has been refining farming practices and developing sustainable agricultural technologies since 1946. The ICAR-Central Rice Research Institute (CRRI), Cuttack, has been at the forefront of rice improvement research for over seven decades. Between 2000 and 2024, a systematic series of experiments was conducted to enhance yield potential, understand physiological determinants of productivity (**Fig. 1**), and explore the role of photosynthesis and growth indices such as Net Assimilation Rate (NAR), Crop Growth Rate (CGR), Leaf Area Index (LAI), and Harvest Index (HI) (Fang et al., 2022).

A fundamental component of this bulletin has involved the detailed characterization of rice genetic resources for traits governing plant growth and yield components. Critical production characteristics, such as panicle length, culm number, grain number per panicle, and single plant yield, have shown significant variations (Meng et al., 2016). The physiological profiling of these rice genotypes has led to targeted improvements, including critical investigations on morpho-physiological traits necessary for designing 'Super Rice' and New Plant Types (NPT). Latest research advances have identified that higher grain yield in New Generation Rice (NGRs) have significant correlation with the photosynthetic rate and the activities of enzymes present in the leaf and stem, and faster remobilization of sucrose through higher number of vascular bundles (Panda et al., 2023). Research on abiotic stress tolerance and breeding for it has been a key focus, requiring a deep understanding of response systems in plants (Gilliam et al., 2017). The identification of physiological marker features linked with submergence tolerance was one of the significant works that addressed water-related stresses (Ram et al., 2002). The Sub1 gene has been effectively used for developing submergence-tolerant cultivars such as CR Dhan 806 (Varshadhan Sub1) and pyramided lines that carry up to seven genes or QTLs, which provide tolerance against bacterial blight, drought and submergence (Mohapatra et al., 2023).

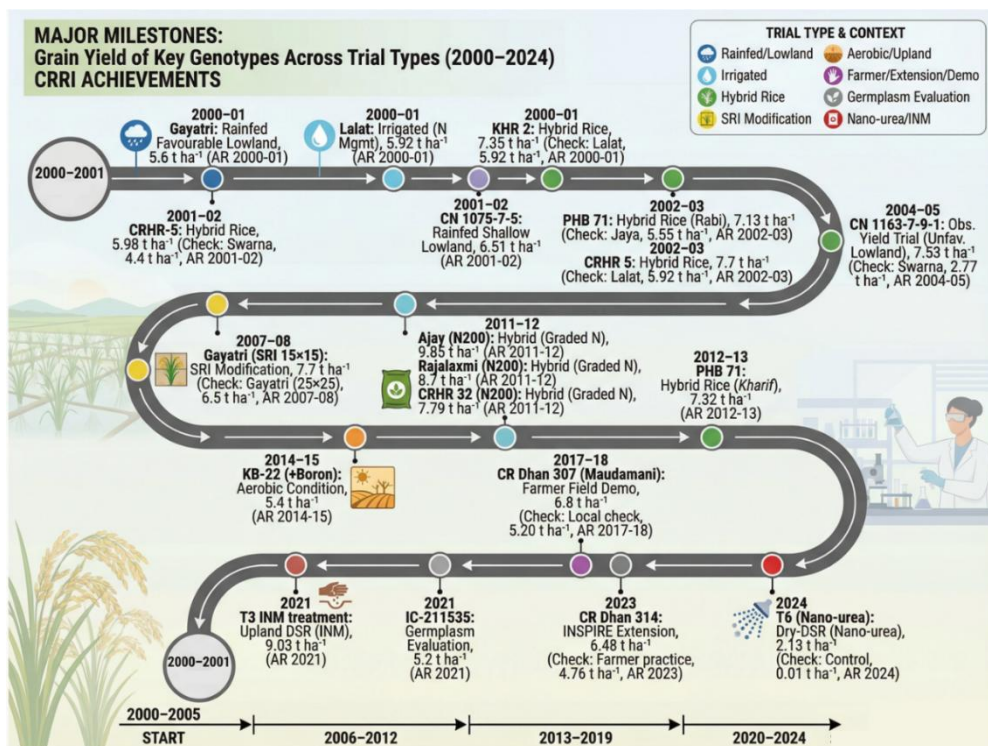


Fig. 1: Historical Yield Progression of Elite Genotypes Serving as a Visual Reference for Understanding Genetic Gains and Identifying Benchmark Varieties for Future Breeding Targets

The studies in drought-prone areas concentrated on analysing recombinant inbred lines (RILs) to discover genotypes with high spikelet fertility under heat stress and identifying effective donors for seedling stage drought tolerance through essential root anatomical characteristics (Zhang et al., 2014). Strategies for mitigating climate change were also physiologically assessed in production systems. For example, Direct Seeded Rice (DSR) was considered as a substitute for conventional transplanted rice as it reduces the flooding duration and the methane emissions (Xu et al., 2019). This effect was linked to variety duration and root architecture traits. Furthermore, studies explored the potential of compounds like boron to mitigate the effect of high temperature in rice (Calderón-Páez et al., 2021). Research was also aimed at improving the nutrient use efficiency (NUE), specifically with regard to Nitrogen (N) and phosphorus (P), simultaneously with environmental challenges (Singh Meena et al., 2022). Studies employed hydroponics and field experiments to identify germplasm donors that exhibited tolerance to low phosphorus conditions, characterized by high shoot and root biomass (Panigrahy et al., 2014).

Plant growth analysis provides a quantitative framework for linking biomass accumulation to final yield (Poorter et al., 2012). The parameters include crop growth rate (CGR), net assimilation rate (NAR), relative growth rate (RGR), leaf area index (LAI), and harvest index (HI). Crop growth rate (CGR) refers

to the rate of dry matter accumulation per unit ground area (Vallabhbhai, 2018). Higher CGR during vegetative and reproductive phases is directly linked with higher yield potential (Takai et al., 2006). Net Assimilation Rate (NAR) represents photosynthetic efficiency per unit leaf area. Genotypes with stable or higher NAR under stress conditions maintain the yield stability (Zhu et al., 2020). Leaf Area Index (LAI) is the ratio of leaf area to ground area, which is an indicator of canopy photosynthetic capacity. Optimal LAI is crucial for maximizing radiation use efficiency (Fang et al., 2019). Relative Growth Rate (RGR) refers to biomass increase relative to existing biomass. It is useful in comparing genotypic performance during early growth (James & Drenovsky, 2007). Harvest Index (HI) is the ratio of economic yield (grain) to total biomass. Hybrids with HI values exceeding 0.50 (PHB 71, CRHR 5) represent significant physiological efficiency (Nayak et al., 2019). Together, these parameters provide a holistic view of how rice plants intercept, convert, and partition resources into yield.

Rice, as a C_3 plant, is inherently limited in photosynthetic efficiency as compared to C_4 crops like maize. Improving photosynthesis is therefore a frontier in rice physiology research. CRRI's work between 2000 and 2024 revealed strong correlations between photosynthetic rate (P_N), chlorophyll content, and grain yield across hybrids and improved varieties and the importance of gas exchange traits (stomatal conductance, transpiration rate, water use efficiency) in determining productivity under different light and moisture conditions (Li et al., 2017). By bridging field agronomy, physiology, and molecular biology, CRRI's photosynthetic experiments have laid the foundation for the next generation of hybrid rice varieties.

Molecular and phenotypic analyses were rigorously applied to target low phosphorus stress tolerance, searching for key genes like PSTOL1 (Sar et al., 2024). Investigations into long-term fertilization regimes provided crucial physiological data on carbon and nitrogen mineralization kinetics in paddy soil, revealing how continuous inorganic and organic applications influence soil bacterial community structure and net rice productivity (Kumar et al., 2018). Another important physiological component addressed early crop establishment, highlighting the significance of seed vigour and invigoration techniques in improving stand establishment and providing a competitive edge over weeds in the early stages of growth. The biotic environment necessitated continuous physiological screening for resistance against major pests and diseases, including blast, bacterial leaf blight (BLB), and brown plant hopper (BPH) (Singh et al., 2020). This effort involved the screening of thousands of germplasm accessions and national nursery entries in controlled and uniform blast nursery (UBN) environments (Vasudevan et al., 2014). Molecular and biochemical characterization provided insights into defence mechanisms, such as the activity of defence enzymes (peroxidase, polyphenol oxidase, catalase) and total phenol content in response to infestation, such as gall midge-induced silver shoot formation (Raman, 2003). Additionally, research explored eco-friendly management using novel strategies, including the elucidation of biocontrol mechanisms and growth promotion potential of bio-agents like *Trichoderma* sp.

These research achievements were underpinned by the strategic application of modern genetics and breeding tools to rapidly translate physiological knowledge into new varieties. Key methodologies included marker-assisted selection (MAS) for pyramiding resistance genes (BLB, Submergence, and drought), wide hybridization utilizing wild species such as *O. longistaminata* (for BLB tolerance) or *O.*

brachyantha (for yellow stem borer resistance), and accelerating breeding cycles through Doubled Haploidy (DH) techniques to produce homozygous lines quickly (Chukwu et al., 2019). Most notably, the cutting-edge technology of CRISPR/Cas9 genome editing has been introduced to precisely target physiological and yield-related genes, such as IPA1, EPFL9, Gn1a, and SD1, further linking advanced physiological understanding with rapid varietal development (Ali & Wani, 2021). The compiled studies reflect a comprehensive and sustained effort over the past decade and a half to understand the complex genetic, physiological, and environmental factors influencing rice growth and production (Jagadish et al., 2012). This bulletin synthesizes two decades of experimental evidence, linking field yield trials with physiological growth analyses and photosynthesis-centred research. Highlighting how yield potential, growth parameters, and photosynthetic efficiency intersect provides a knowledge framework for future breeding programs aimed at climate-resilient, resource-efficient, and high-yielding rice systems.

2: Yield and Productivity Experiments Providing Empirical Evidence for Genotype Selection and Agronomic Optimization

Enhancing yield has been the foremost goal of rice research at ICAR-CRRI, Cuttack. Between 2000 and 2024, a broad range of field trials, farmer demonstrations, and station experiments were conducted to evaluate new genotypes, hybrids, and management practices under diverse ecologies (Fig. 2). These studies provide not only data on yield performance but also insights into how nutrient management, agronomic practices, and genotype selection influence productivity. By systematically recording yields across rainfed lowlands, irrigated ecosystems, aerobic systems, and direct-seeded rice (DSR), CRRI has built a robust evidence base showing how rice productivity can be enhanced sustainably.

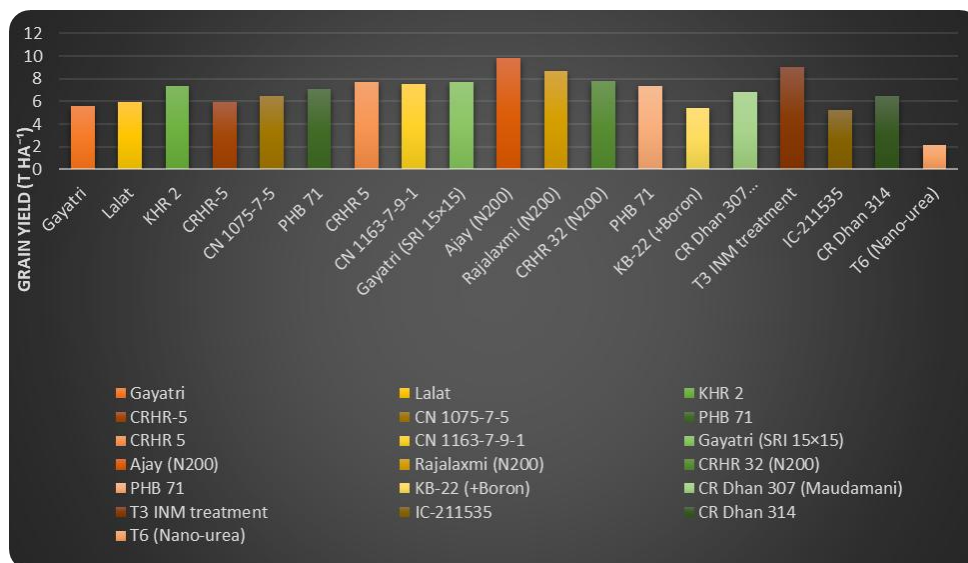


Fig. 2: Grain Yield of Key Genotypes screened during 2000–2024 for yield and productivity

2.1 Nutrient Management Strategies and Hybrid Performance as Guidelines for Maximizing Yield Potential in Diverse Ecologies

The 2000-2003 period marked intensive research into Nitrogen (N) management and hybrid rice performance. In 2000-01, experiments with the variety Gayatri under rainfed favourable lowlands at Cuttack demonstrated the effectiveness of integrated N management (INM). By combining green manure (N30) with SPAD-based N application (N10), researchers achieved yields of 5.6 t ha⁻¹, with N uptake rising to 92.8 kg ha⁻¹ compared to the control (71.5 kg ha⁻¹). This underscored the importance of synchronizing N supply with crop demand. In irrigated trials the same year, the popular variety Lalat was tested with 120 kg N ha⁻¹ applied in four equal splits (transplanting, seedling establishment, active tillering, panicle initiation). This resulted in yields of 5.92 t ha⁻¹, with improved panicle weight (2.05 g) and total dry matter (10.5 t ha⁻¹).

Hybrid rice gained attention in 2001-02 with CRHR-5, which yielded 5.98 t ha⁻¹ under shallow lowland conditions, surpassing traditional checks like Jaya (4.69 t ha⁻¹) and Swarna (4.40 t ha⁻¹). Similarly, CN 1075-7-5, a late-duration genotype tested in the DRR-IVT trial, achieved 6.51 t ha⁻¹, the highest among 46 entries. By 2002-03, hybrids like PHB 71 demonstrated remarkable yield potential, achieving 7.13 t ha⁻¹ under irrigated rabi conditions with 120:60:40 NPK management. Two distinct lessons emerged from these early findings: first, hybrids consistently performed better than conventional types; second, yields across ecologies were improved by precise nitrogen control through timing and integration with organic sources (Table 1).

Table 1: Nitrogen Uptake and Grain Yield Associations as a Reference Guide for Optimizing Nutrient Management and Selecting High Nitrogen-Use Efficient Genotypes in Rice Breeding Programs

Variety / Genotype	Year	N Uptake (kg ha ⁻¹)	Grain Yield (t ha ⁻¹)	Reference
Gayatri (Control)	2000-01	71.5	5	AR 2000-01
Gayatri (INM)	2000-01	92.8	5.6	AR 2000-01
Gayatri (GM+SPAD)	2000-01	104.6	5.6	AR 2000-01
Savitri (Coated urea)	2000-01	106.5	6.6	AR 2000-01
IR 36 (N timing)	2000-01	118.7	7.2	AR 2000-01
PA 6201 (75% basal)	2000-01	120.6	7.38	AR 2000-01
Naveen (GreenSeeker)	2022	95	6.1	AR 2022
T1 Nano-urea (DSR)	2024	54.6	2.83	AR 2024

The 2004–2008 period witnessed notable breakthroughs in both genotype performance and agronomic innovations. In 2004-05, the genotype CN 1163-7-9-1 recorded the highest yield (7.53 t ha⁻¹) in unfavourable lowlands under observational yield trials. The check variety Swarna, by contrast, yielded only 2.77 t ha⁻¹, highlighting the untapped potential of new breeding lines in stress-prone ecologies. A landmark experiment in 2007-08 introduced System of Rice Intensification (SRI) modifications. The variety Gayatri, when transplanted under close spacing (15 × 15 cm), produced a yield of 7.7 t ha⁻¹. Wider

spacing (25 × 25 cm) led to a decline in yield to 6.5 t ha⁻¹, showing that optimized planting geometry maximizes tillering and panicle density. Together, these studies reinforced the message that genetic gains need to be complemented with fine-tuned agronomic practices, especially under resource-constrained environments.

2.2 Hybrid Resilience Under Biotic and Abiotic Stress Offering Insights for Developing Climate-Smart and Disease-Resistant Varieties

The 2010-2015 period expanded the scope of yield experiments by integrating disease management and stress physiology. In 2012-13, hybrid PHB 71 under irrigated kharif conditions achieved the highest yield of 7.32 t ha⁻¹, despite a mean false smut incidence of 41.03%. Importantly, it produced the highest clean grain yield, suggesting that hybrids can maintain productivity even under biotic stress pressures. In 2014-15, under aerobic conditions, the genotype KB-22 responded favourably to boron application (2 kg ha⁻¹). Grain yield reached 5.40 t ha⁻¹, with an optimal filled grain percentage (78%) even under high-temperature stress.

By 2015-16, CRRI began assessing cropping system productivity. A rice-maize-cowpea sequence under integrated nutrient management achieved the highest system productivity of 17.30 t ha⁻¹, proving that rice-based intensification enhances overall land use efficiency beyond single season yields. In 2017-18, the genotype CR 4007-547-11-2-1-2-3-3 recorded the highest grain yield of 5.34 t ha⁻¹ under aerobic advanced yield trials, outperforming the check variety Pyari (4.22 t ha⁻¹). In parallel farmer field trials, the variety CR Dhan 307 (Maudamani) achieved 6.80 t ha⁻¹, representing a 30.77% yield advantage over local checks. Such farmer-level validations bridge the gap between experimental station trials and real-world adoption, reinforcing the importance of participatory breeding and demonstration models (Table 2).

Table 2: Yield Performance Across Diverse Ecologies Providing Baseline Data for Ecology-Specific Varietal Selection and Targeted Breeding for Rainfed, Irrigated, Aerobic, and Direct-Seeded Rice Systems

Ecology / Trial Category	Period	Min Yield (t ha ⁻¹)	Max Yield (t ha ⁻¹)	Best Genotype	Key Management Factor
Rainfed Favourable Lowland	2000–2010	5.6	7.53	CN 1163-7-9-1	Integrated N management (INM)
Irrigated (Inbred)	2000–2024	5.12	7.32	Lalat, Naveen	Split N application (120 kg N ha ⁻¹)
Hybrid Rice	2000–2015	5.98	9.85	Ajay, PHB 71	High N up to 200 kg N ha ⁻¹
Aerobic Conditions	2006–2021	2.63	5.4	KB-22	Boron + precision N management
Direct Seeded Rice (DSR)	2021–2024	2.13	9.03	T3 INM treatment	Organic + inorganic N integration
Farmer Field Demonstrations	2017–2023	6.48	6.8	CR Dhan 307, CR Dhan 314	INSPIRE extension model

2.3 Integrated Nutrient Management and Precision Agriculture Tools as Pathways Toward Sustainable and Resource-Efficient Rice Production

The 2020s mark a new phase of technological sophistication, focusing on precision nutrient management and eco-friendly inputs. In 2021, upland direct seeded rice (DSR) trials under integrated nutrient management (INM) achieved remarkable productivity. Treatments combining Recommended Dose of Fertilizers (RDF), 25% N from green manure, 25% N from farmyard manure (FYM) yielded 9.03 t ha⁻¹, with associated improvements in grains per panicle (164) and tiller density (273 m⁻²). This finding highlighted the synergy between organic and inorganic nutrient sources for maximizing DSR productivity.

In 2022, precision N management using green seeker-based recommendations improved yields of the variety Naveen by 4.7–7.1% compared to blanket N applications. This demonstrated the potential of site-specific nutrient management (SSNM) tools in fine-tuning crop N supply. The INSPIRE extension model in 2023 showcased the variety CR Dhan 314 across 305 farmer demonstrations. Average yields reached 6.48 t ha⁻¹, providing a 36.07% advantage over farmer's practice varieties. The results underscored the extension value of CRRI's research and its ability to deliver tangible yield gains at scale. In 2024, dry-direct seeded rice (DSR) experiments tested nano-urea applications with LCC-based N management. The best treatment achieved was 2.13 t ha⁻¹, which was a 1.11-fold increase over control plots, demonstrating the yield-enhancing role of nano-fertilizers under challenging rainfed DSR conditions (Table 3).

Table 3: Comprehensive Yield and Management Database Serving as a Ready Reference for Identifying Superior Genotypes, Optimal Agronomic Practices, and Potential Donors for Yield Enhancement Breeding

Year	Ecology/Trial	Variety/Genotype	Location/Context	Management Practice	Key Yield Finding	Associated Metric	Ref.
2000-01	Rainfed Favourable Lowland	Gayatri	Cuttack (INM)	GM+SPAD-N	5.6 t/ha	N uptake 92.8 kg/ha	AR 2000-01
2000-01	Irrigated (N Mgmt)	Lalat	Standard Package	120 kg N/ha splits	5.92 t/ha	Panicle wt 2.05g, TDM 10.5 t/ha	AR 2000-01
2001-02	Hybrid Rice	CRHR-5	Shallow Lowland	Standard NPK	5.98 t/ha	Surpassed Jaya, Swarna, Tapaswini	AR 2001-02
2001-02	Rainfed Shallow Lowland	CN 1075-7-5	DRR Trial (IVT)	Standard practices	6.51 t/ha	Highest among 46 late duration genotypes	AR 2001-02
2002-03	Hybrid Rice	PHB 71	Irrigated (Rabi/DS)	120:60:40 NPK/ha	7.13 t/ha	Higher than Jaya, Chandrama	AR 2002-03

Year	Ecology/Trial	Variety/Genotype	Location/Context	Management Practice	Key Yield Finding	Associated Metric	Ref.
2004-05	Unfavourable Lowland	CN 1163-7-9-1	OYT	Standard	7.53 t/ha	Swarna yielded 2.77 t/ha	AR 2004-05
2007-08	Irrigated/Boro	Gayatri	Field Expt	15x15 cm	7.7 t/ha	25x25 cm gave 6.5 t/ha	AR 2007-08
2012-13	Hybrid Rice	PHB 71	Irrigated Kharif	120:60:40 NPK	7.32 t/ha	Smut incidence 41.03%	AR 2012-13
2014-15	Aerobic	KB-22	Station Trial	2 kg/ha Boron	5.40 t/ha	78% filled grains under heat	AR 2014-15
2015-16	Cropping System	Rice-Maize-Cowpea	Integrated Farming	RDF+SM	17.30 t/ha system	Highest land use efficiency	AR 2015-16
2017-18	Aerobic (AYT)	CR 4007-....-3-3	AYT	Aerobic	5.34 t/ha	Outperformed Pyari (4.22 t/ha)	AR 2017-18
2017-18	Varietal Demo	CR Dhan 307 (Maudamani)	Farmer fields	Farmers practices	6.80 t/ha	30.77% yield advantage	AR 2017-18
2021	Upland DSR	T3 INM treatment	INM	RDF+25%N-GM+25%N-FYM	9.03 t/ha	164 grains/panicle, 273 tillers/m ²	AR 2021
2022	Precision N Mgmt	Naveen	SSNM	GreenSeeker	4.7–7.1% enhancement	Over blanket N application	AR 2022
2023	INSPIRE Model	CR Dhan 314	305 Demos	Demonstrated variety	6.48 t/ha	36.07% yield advantage	AR 2023
2024	Dry-DSR	T6 treatment	LCC+Nano-urea	Nano-urea	2.13 t/ha	1.11× over control	AR 2024

3: Growth and Physiological Parameters in Rice Productivity Establishing Benchmarks for Phenotypic Selection and Ideotype Design

Yield in rice is not determined solely by the number of grains per panicle or panicle density but is the cumulative outcome of physiological growth processes. Growth analysis provides a quantitative framework to explain how rice plants intercept solar radiation, assimilate carbon, partition dry matter, and convert biomass into grain yield. ICAR-CRRI's long-term investigations (2000-2024) systematically quantified parameters such as crop growth rate (CGR), net assimilation rate (NAR), leaf area index (LAI),

relative growth rate (RGR), and harvest index (HI). Together, these indices provided insights into the physiological underpinnings of yield differences across varieties, hybrids, and management practices (Table 4).

Table 4: Physiological Benchmarks for Rice Improvement Presenting Reference Values of CGR, NAR, HI, LAI, and Stress Tolerance Traits for Phenotypic Selection and Ideotype Breeding

Parameter	Best Recorded Value	Genotype / Context	Stage / Condition	Implication	Reference
Crop Growth Rate (CGR)	9.2 g m ⁻² day ⁻¹	Gayatri, Ratna, Savitri	Flowering; 120 kg N ha ⁻¹	Higher CGR at flowering linked to yield	CRRI AR 2002-03
Harvest Index (HI)	0.53	PHB 71, KHR 2	Maturity; irrigated kharif	HI >0.50 benchmark for elite hybrids	CRRI AR 2000-01/2002-03
Leaf Area (peak)	22.3 cm ² per leaf	RR 354-1	Vegetative; P management trial	Correlated with superior mean yield (3.42 t ha ⁻¹)	CRRI AR 2003-04
Relative Water Content (RWC)	71.6% (under -8 bar)	IET 18235	Drought stress	Sustained RWC indicates drought tolerance	CRRI AR 2004-05
Chlorophyll Fluorescence	r ² =92–96% with survival	IR 42, IR 72, Ganga	4–6 days submergence	Non-destructive marker for sub. tolerance screening	CRRI AR 2006-07
Root Length Density (RLD)	1.96 cm cm ⁻³	BADAJANGIA	Drought condition	Highest RLD confers superior water uptake	CRRI AR 2021
Root Volume (RV)	13.15 cc	TAGUR	Drought condition	Larger root volume supports resource acquisition	CRRI AR 2021
Photosynthetic Rate (P _N)	27.8 μmol m ⁻² s ⁻¹	CR 4336-13-1-1-2	Vegetative/Flowering (NGR)	Highest P _N among NGRs; positively correlated with yield	CRRI AR 2022
Tiller density	273 tillers m ⁻²	T3 INM treatment	DSR upland	Associated with highest grain yield (9.03 t ha ⁻¹) in DSR	CRRI AR 2021

Parameter	Best Recorded Value	Genotype / Context	Stage / Condition	Implication	Reference
N Uptake	120.6 kg ha ⁻¹	PA 6201 (75% basal)	Panicle emergence–booting	Synchronized N supply maximizes photosynthetic capacity	CRRI AR 2000-01

3.1 Crop Growth Rate and Net Assimilation Rate as Indicators of Biomass Accumulation Efficiency for Yield Prediction and Genotype Screening

CGR reflects the rate of dry matter accumulation per unit ground area, while NAR represents the efficiency of photosynthesis per unit leaf area. Both parameters are central to understanding how crops translate solar energy into yield. In 2002-03, CRRI studies revealed that Gayatri, Ratna, and Savitri maintained leaf photosynthetic rates above 35 kg CO₂ ha⁻¹ hr⁻¹ when supplied with 120 kg N ha⁻¹. This resulted in higher CGR values during flowering (ranging from 4.1 to 9.2 g m⁻² day⁻¹), directly correlating with superior yields. Hybrid genotypes consistently exhibited higher NAR compared to inbred checks. For instance, Ajay, Rajalaxmi, and CRHR 32, when supplied with graded nitrogen levels up to 200 kg N ha⁻¹, displayed a linear increase in NAR and CGR, culminating in yields up to 9.85 t ha⁻¹ (Ajay). Under stress-prone environments, genotypes with stable NAR values-maintained productivity. For example, drought-tolerant lines like IET 18235 maintained Relative Water Content (RWC) at 71.6% under -8 bar stress, helping sustain NAR and dry matter accumulation even under severe moisture stress. These results affirm that sustained NAR under stress and maximized CGR during critical growth stages (tillering to flowering) are decisive for yield enhancement (**Table 5**).

Table 5: Crop Growth Rate (CGR) at Key Phenological Stages

Variety / Genotype	Type	CGR Tillering (g m ⁻² day ⁻¹)	CGR Flowering (g m ⁻² day ⁻¹)	CGR Grain Fill (g m ⁻² day ⁻¹)
Gayatri	Inbred	3.5	6.2	4
Ratna	Inbred	3.2	6.8	4.1
Savitri	Inbred	3.0	5.9	3.8
PHB 71	Hybrid	4.2	8.5	5.5
CRHR 5	Hybrid	4.0	9.2	5.8

Variety / Genotype	Type	CGR Tillering (g m ⁻² day ⁻¹)	CGR Flowering (g m ⁻² day ⁻¹)	CGR Grain Fill (g m ⁻² day ⁻¹)
Ajay (N200)	Hybrid	5.0	9.0	6.1
Rajalaxmi (N200)	Hybrid	4.5	8.2	5.6

3.2 Leaf Area Index and Canopy Dynamics Influencing Light Interception and Radiation Use Efficiency for Optimizing Plant Architecture

LAI quantifies the leaf area relative to ground surface, a determinant of canopy photosynthetic capacity and light interception. CRRI studies established that an optimal LAI of 4-6 during peak growth stages maximizes radiation use efficiency in rice. In phosphorus management trials (2003-04), the genotype RR 354-1 exhibited the highest leaf area (22.3 cm²), which correlated with superior mean yield (3.42 t ha⁻¹) across P levels. Experiments under low light conditions (2014-15) revealed that genotypes such as Kalinga II, Konark, and Satyakrishna maintained higher chlorophyll b accumulation and leaf expansion, enabling them to preserve LAI and photosynthetic efficiency under suboptimal light. In aerobic conditions (2006-07), hybrids like CRHR 5 showed a 26.5% increase in yield response to N compared to 40 kg N ha⁻¹ baseline, partly due to their ability to sustain higher LAI and canopy assimilation under reduced water availability. Thus, maintaining optimal LAI under stress ecologies emerges as a key physiological trait for sustaining yield.

3.3 Dry Matter Partitioning and Harvest Index as Key Determinants of Source-Sink Balance for Selecting High Grain-Filling Genotypes

The efficiency with which assimilates are partitioned between vegetative organs and grains is captured by the Harvest Index (HI). High HI values signify a greater proportion of biomass allocated to grains, directly contributing to yield. In 2000-01, hybrids KHR 2 and PHB 71 achieved total dry matter (TDM) of 14.6 and 14.2 t ha⁻¹, respectively, with HI values of 0.50 and 0.53. This level of partitioning efficiency translated into grain yields exceeding 7.3 t ha⁻¹, significantly outperforming inbred checks. By 2002-03, hybrids like CRHR 5 recorded TDM of 1086 g m⁻² with an HI of 0.48, while PHB 71 recorded slightly lower biomass (905 g m⁻²) but a higher HI of 0.53. This demonstrates the trade-off between biomass production and partitioning efficiency, where both pathways can lead to high yields. In 2010-11, straw integration studies with Gayatri revealed that incorporation of 2.5 t ha⁻¹ rice straw + 60 kg N ha⁻¹ urea produced yields of 5.93 t ha⁻¹, showing how improved soil organic matter enhances dry matter production and partitioning. In 2021, the accession IC-211535 achieved a grain yield of 5.20 t ha⁻¹, supported by high biomass (10.37 t ha⁻¹) and an HI of 0.50. Across studies, HI values above 0.50 consistently marked high-yielding genotypes, confirming its role as a key physiological target in rice breeding.

3.4 Relative Growth Rate (RGR) and Phenological Adjustments

RGR captures the relative increase in plant biomass over time and is particularly useful in early growth stages. In 2000-01, phenological studies revealed that direct-seeded rice shortened its total growth duration by 28 days compared to transplanted rice. This accelerated growth rate provided a competitive advantage under late sowing and stress-prone conditions. Screening of photo-insensitive varieties showed that late-sown rice maintained competitive RGR values, producing higher yields despite shortened crop duration. In black rice germplasm evaluations (2019), several lines combined drought tolerance with stable growth rates, maintaining biomass accumulation under both drought and submergence stress. These findings suggest that stable RGR under shortened or stress-prone growth durations is a valuable adaptation trait.

3.5 Relative Growth Rate and Phenological Plasticity Enabling Adaptation to Variable Growing Conditions and Shortened Crop Durations

Root growth traits play a decisive role in water and nutrient acquisition, directly influencing aboveground growth indices. In 2021, CRRI evaluated root length density (RLD) and root volume (RV) under drought. The landrace BADAJANGIA exhibited the highest RLD (1.96 cm cm^{-3}), while TAGUR recorded the maximum RV (13.15 cm cm^{-3}). Both traits conferred better drought resilience by supporting biomass accumulation and yield. Earlier, in 2002-03, studies showed that root oxidation activity (ROA) was negatively correlated with methane emissions. Varieties like K39 and Ratna had high ROA, reducing methane emissions, while Lalat recorded the lowest emissions. This highlighted the dual benefit of root traits for both yield stability and environmental sustainability.

3.6 Stress Physiology and Growth Indices Providing Reliable Markers for Screening and Selecting Abiotic Stress-Tolerant Germplasm

Abiotic stress tolerance is intrinsically linked to growth parameters such as RWC, CGR, and NAR. In submergence tolerance studies (2004-05), non-destructive techniques like chlorophyll fluorescence spectrophotometry identified tolerant entries such as Sarala, Gayatri, and IR 42, which maintained higher green leaf area and ET_0/ABS ratios, sustaining photosynthesis and growth under flooding. Under high-temperature stress (2006-07), genotypes like IR 72 and Annapurna showed significant reductions in spikelet per m^2 and fertility when temperatures rose by $\sim 19^\circ\text{C}$ during grain filling, linking thermal sensitivity to disrupted growth indices. Sub1 gene (2012-13) introduction into IR 64 backgrounds maintained photosynthetic capacity and CGR during re-aeration, stabilizing yields during submergence. Together, these findings demonstrate how growth indices provide reliable markers of stress resilience, guiding breeding efforts for resilience rice varieties.

3.7 Photosynthetic Studies Linking Carbon Assimilation Efficiency with Yield Enhancement and Stress Resilience in Rice

ICAR-CRRI has dedicated over two decades (2000–2024) to quantifying, enhancing, and engineering rice photosynthetic traits. These efforts span from field-level physiological studies on nitrogen management and gas exchange to advanced molecular approaches, such as the introduction of C_4 pathway genes and carbonic anhydrase (CA) transgenes. Together, these studies offer a holistic view

of how photosynthesis can be harnessed to sustain and enhance rice productivity under diverse ecologies and climate challenges (**Table 6**).

Table 6: Stage-Wise Crop Growth Rate in Hybrids and Inbreds Offering Selection Criteria for Identifying Genotypes with Superior Biomass Accumulation Potential for Yield Maximization

Year	Study Focus / Condition	Genotype / Accession	Growth Stage(s)	Key Physiological Metrics & Values	Production Metric (Yield/Biomass)	Reference
2000-01	N Mgmt (Coated Urea)	Savitri	Tillering to maturity	N uptake (T5): 106.5 kg ha ⁻¹ ; Panicles: 316 m ⁻²	Grain yield (T8): 6.6 t ha ⁻¹	AR 2000-01
2000-01	N Mgmt (Integrated)	Gayatri	Vegetative to maturity	N uptake (GM+N splits): 104.6 kg ha ⁻¹	Grain yield: 5.6 t ha ⁻¹	AR 2000-01
2000-01	Hybrid N Timing	PA 6201, IR 36	Panicle emergence–booting	N uptake: PA 6201=120.6; IR 36=118.7 kg ha ⁻¹	PA 6201=7.38 t ha ⁻¹	AR 2000-01
2000-01	Hybrid DM Partitioning	KHR 2, PHB 71	Maturity	TDM: KHR 2=14.6, PHB 71=14.2 t ha ⁻¹ ; HI: 0.50–0.53	Grain yield: KHR 2=7.35 t ha ⁻¹	AR 2000-01
2001-02	Photosynthesis (P _N) goal	Swarnaprabha, IR 36, Ratna, Gayatri	Vegetative/Flowering	Min P _N : 32 kg CO ₂ ha ⁻¹ hr ⁻¹ ; Max P _N at 60 kg N ha ⁻¹	TDM >14 t ha ⁻¹ (long-duration)	AR 2001-02
2001-02	Chlorophyll–N status	Ranajit, Savitri, Swarna	Flowering	20% higher chlorophyll; SPAD correlated with leaf N	Yield: 5.12–6.27 t ha ⁻¹ at 80 kg N ha ⁻¹	AR 2001-02
2002-03	N-use efficiency	PHB 71, CRHR 5 vs. Low N lines	Flowering	Phys. efficiency: 140–150 (High N) vs. 109–135 (Low N)	Yield: 6.00–7.14 t ha ⁻¹ vs. 3.15–5.07 t ha ⁻¹	AR 2002-03

Year	Study Focus / Condition	Genotype / Accession	Growth Stage(s)	Key Physiological Metrics & Values	Production Metric (Yield/Biomass)	Reference
2002-03	P_N and CGR	Gayatri, Ratna, Savitri	Flowering	$P_N > 35 \text{ kg CO}_2 \text{ ha}^{-1} \text{ hr}^{-1}$; CGR: $4.1\text{--}9.2 \text{ g m}^{-2} \text{ day}^{-1}$	Higher yields under 120 kg N ha^{-1}	AR 2002-03
2002-03	Hybrid yield potential	PHB 71, CRHR 5, PA 6201	Maturity	TDM: CRHR 5= 1086 g m^{-2} , PHB 71= 905 g m^{-2} ; HI: $0.48\text{--}0.53$	Yield: CRHR 5= 7.7 , PHB 71= 7.8 t ha^{-1}	AR 2002-03
2003-04	P management & pigments	Anjali, RR 354-1, Vandana	Vegetative	SPAD: Anjali= 39.4 ; Leaf area: RR 354-1= 22.3 cm^2	Mean yield: RR 354-1= 3.42 t ha^{-1}	AR 2003-04
2004-05	Drought screening (RWC)	IET 18235, IET 17540, Savitri, Vandana	Vegetative/Flowering	RWC (at -8 bar): IET 18235= 71.6%	TDM (Savitri): 749 g m^{-2}	AR 2004-05
2004-05	Hybrid grain filling	CRHR 5, PHB 71, KRH 2	Grain filling	TDM (CRHR 5): 1473 g m^{-2} ; $<35\%$ reduction in P_N	Yield: CRHR 5= 7.6 t ha^{-1} vs. Lalat= 5.1 t ha^{-1}	AR 2004-05
2006-07	Chlorophyll fluorescence (Sub.)	IR 42, IR 72, Ganga	Submergence	High ET_0/ABS ratio; green leaf retention $r^2=92\text{--}96\%$ with survival	Survival focus	AR 2006-07
2006-07	N response (Aerobic)	KRH 2, CRHR 5, Naveen, IR 64	Vegetative/Flowering	N-response: KRH 2= $+15.4\%$; CRHR 5= $+26.5\%$ over 40 kg N baseline	Yield: KRH 2= 2.61 , CRHR 5= 2.63 t ha^{-1}	AR 2006-07
2010-11	N mgmt (Straw integration)	Gayatri	Maturity	2.5 t ha^{-1} straw + 60 kg N urea	Grain yield (max): 5.93 t ha^{-1}	AR 2010-11

Year	Study Focus / Condition	Genotype / Accession	Growth Stage(s)	Key Physiological Metrics & Values	Production Metric (Yield/Biomass)	Reference
2011-12	P_N vs. graded N (0–200 kg N)	Ajay (Hybrid)	Vegetative/Flowering	P_N increased linearly with N; $P_N \text{ Chl}^{-1}$ higher at N200	Yield: 9.85 t ha ⁻¹	AR 2011-12
2011-12	P_N vs. graded N (0–200 kg N)	Rajalaxmi (Hybrid)	Vegetative/Flowering	Similar to Ajay; P_N and $P_N \text{ Chl}^{-1}$ higher at N200	Yield: 8.70 t ha ⁻¹	AR 2011-12
2011-12	P_N vs. graded N (0–200 kg N)	CRHR 32 (Hybrid)	Vegetative/Flowering	Similar response to Ajay and Rajalaxmi	Yield: 7.79 t ha ⁻¹	AR 2011-12
2011-12	Submergence (QTL Sub1 effect)	Sub1 NILs (e.g., Swarna Sub1)	Submergence/recovery	Chl. fluorescence (OJIP) showed improved recovery	—	AR 2011-12
2014-15	Low light response	Kalinga II, Konark, Satyakrishna	Vegetative/Flowering	Higher chlorophyll b and P_N maintained under low light	Sustained yield stability	AR 2014-15
2016-17	Gas exchange (Low vs. normal light)	CR Dhan 401, Satyabhama	Vegetative	P_N : 22.2→12.5 (CR Dhan 401), 20.8→12.8 (Satyabhama); WUE increased	—	AR 2016-17
2017-18	C_4 pathway transgenics	Transgenic rice lines	Vegetative	Transformation with SiPPDK, SiME, SiPEPC, SBiC genes	Enhanced photosynthetic efficiency	AR 2017-18

Year	Study Focus / Condition	Genotype / Accession	Growth Stage(s)	Key Physiological Metrics & Values	Production Metric (Yield/Biomass)	Reference
2018-19	Transgenic SbCA gene	IR 64 background (SbCA)	Vegetative/Flowering	CA activity: 19–47 units μg^{-1} protein (vs. control 8.9–10.1); P_N higher	Improved productivity over controls	AR 2018-19
2019	Transgenic SiPPDK (Setaria italica)	Plant No. 26	Flowering	Highest P_N among tested; strong enzyme activity	Higher productivity than controls	AR 2019
2021	Biomass and HI evaluation	IC-211535	Maturity	Biomass: 10.37 t ha ⁻¹ ; HI = 0.50	Grain yield: 5.20 t ha ⁻¹	AR 2021
2022	New Generation Rice (NGRs)	CR 4336-13-1-1-2, CR 4030-3-3-3-1-1, CR Dhan 328	Vegetative/Flowering	P_N : CR 4336=27.8; CR 4030=25.3; CR Dhan 328=24.2 $\mu\text{mol m}^{-2} \text{s}^{-1}$	High biomass & seed yield; positive correlation with P_N	AR 2022
2023	Transgenic SiPEPC (IR 64)	Line P-7-3	Vegetative	PEPC activity $\uparrow$ 2.2–6.4 $\times$; expression up to 9.1-fold higher	—	AR 2023
2024	Nano-urea (Rainfed DSR)	Treatments T1–T4	Vegetative/Flowering	Grain N uptake: 29.4 (T1) kg ha ⁻¹ ; Total N uptake: 54.6 kg ha ⁻¹	Yield: 2.83 t ha ⁻¹ (T1), 111.2% > Control	AR 2024

3.8 Nitrogen Management and Photosynthetic Efficiency Demonstrating the Role of Nutrient Synchronization in Maximizing Canopy Productivity

Nitrogen is central to photosynthetic machinery, influencing chlorophyll content, Rubisco activity, and canopy photosynthetic rate (P_N). In 2000–01, trials with Savitri using coated urea treatments recorded N uptake up to 106.5 kg ha⁻¹, with panicle density reaching 316 per m². This translated into grain yields of 6.6 t ha⁻¹. Similarly, Gayatri achieved N uptake of 104.6 kg ha⁻¹ under integrated N management, producing yields of 5.6 t ha⁻¹. These findings demonstrated that synchronized N supply maintains higher photosynthetic capacity. Hybrid rice studies revealed how N timing influences photosynthesis. PA 6201,

under 75% basal N application split across panicle emergence (PE), panicle initiation (PI), and booting (BO), achieved N uptake up to 120.6 kg ha⁻¹ and grain yields of 7.38 t ha⁻¹.

In 2001–02, CRRI established that photosynthetic rates must not fall below 32 kg CO₂ ha⁻¹ hr⁻¹ for sustainable yield formation. Varieties like Swarnaprabha, IR 36, Ratna, and Gayatri attained maximum P_N at 60 kg N ha⁻¹, with total dry matter (TDM) exceeding 14 t ha⁻¹ in long-duration types. By 2011–12, hybrids such as Ajay, Rajalaxmi, and CRHR 32 showed a linear increase in P_N from N₀ to N₂₀₀. Ajay reached the highest yield of 9.85 t ha⁻¹ at N₂₀₀, with strong positive correlations between TDM, P_N , and yield. In recent years, precision N tools have refined this linkage. The Greenseeker-based recommendations in 2022 enhanced yields of Naveen by 4.7–7.1% compared to blanket N, while nano-urea trials in 2024 under rainfed DSR increased grain N uptake to 29.4 kg ha⁻¹ and yields to 2.83 t ha⁻¹, representing a 111.2% increase over control. Together, these results highlight that Nitrogen driven photosynthetic enhancement remains a cornerstone of yield stability (Table 7).

Table 7: Genotype-Specific Photosynthetic Rates Under Variable Conditions Providing Reference Data for Breeding Rice with Enhanced Carbon Assimilation and Stress-Resilient Photosynthetic Machinery

Year	Genotype / Line	Type	Light Condition	P_N (μmol m ⁻² s ⁻¹)	Grain Yield (t ha ⁻¹)	Reference
2001-02	Swarnaprabha, IR 36, Ratna	Inbred	Normal	≥32 kg CO ₂ ha ⁻¹ hr ⁻¹	>14 TDM	AR 2001-02
2002-03	Gayatri, Ratna, Savitri	Inbred	Normal (120N)	35	Higher	AR 2002-03
2004-05	CRHR 5	Hybrid	Normal	35	7.6	AR 2004-05
2016-17	CR Dhan 401	Inbred	Normal light	22.2	—	AR 2016-17
2016-17	CR Dhan 401	Inbred	Low light	12.5	—	AR 2016-17
2016-17	Satyabhama	Inbred	Normal light	20.8	—	AR 2016-17
2016-17	Satyabhama	Inbred	Low light	12.8	—	AR 2016-17
2018-19	SbCA transgenic line	Transgenic	Normal	33	Higher	AR 2018-19
2019	SiPPDK plant No. 26	Transgenic	Normal	Highest	Higher	AR 2019
2022	CR 4336-13-1-1-2	NGR	Normal	27.8	High	AR 2022
2022	CR 4030-3-3-3-1-1-1	NGR	Normal	25.3	High	AR 2022
2022	CR Dhan 328	NGR	Normal	24.2	High	AR 2022

3.9 Chlorophyll Content and Fluorescence Dynamics as Non-Destructive Tools for Assessing Photosynthetic Health and Stress Tolerance

Chlorophyll concentration and fluorescence properties directly reflect the health and efficiency of the photosynthetic apparatus. In 2001–02, high N-responsive varieties recorded 20% higher chlorophyll

content, with SPAD readings strongly correlating with leaf N concentration. Yields of Ranajit, Savitri, and Swarna ranged between 5.12 and 6.27 t ha⁻¹ at 80 kg N ha⁻¹, underscoring the tight linkage between chlorophyll, N status, and productivity. Studies in 2006–07 explored chlorophyll fluorescence under submergence in varieties such as IR 42, IR 72, and Ganga. Retention of green leaf area and high ET₀/ABS ratios showed strong correlations (92–96%) with survival under 4–6 days of flooding. This non-destructive technique became a valuable physiological marker for identifying submergence-tolerant germplasm.

Under low-light conditions (2014–15), genotypes like Kalinga II, Konark, and Satyakrishna accumulated higher chlorophyll b, enabling them to capture diffuse light more efficiently. By maintaining canopy photosynthesis under shaded environments, these varieties sustained yield stability where light was a limiting factor. In 2016–17, gas exchange studies compared genotypes under normal vs. low light. CR-Dhan 401 recorded P_N of 22.2 $\mu\text{mol m}^{-2} \text{s}^{-1}$ under normal light, dropping to 12.5 $\mu\text{mol m}^{-2} \text{s}^{-1}$ under low light, while stomatal conductance fell from 1.09 to 0.28 mol H₂O m⁻² s⁻¹. Interestingly, water use efficiency (WUE) increased under low light (2.20 compared to 1.31), suggesting an adaptive trade-off. These findings emphasize how chlorophyll dynamics and fluorescence serve as reliable indicators of stress adaptation, guiding both physiological research and breeding.

3.10 Dry Matter Partitioning and Sustained Photosynthesis During Reproductive Stages Ensuring Efficient Grain Filling and Yield Stability

Efficient partitioning of photosynthates between vegetative organs and grains is crucial for yield. Hybrids such as KRH 2, PHB 71, and CRHR 5 recorded TDM exceeding 1000 g m⁻², with HI values of 0.48–0.53, ensuring grain yields above 7.5 t ha⁻¹. These high HI values reflect efficient remobilization of assimilates during grain filling. In 2004–05, CRHR 5 produced 1473 g m⁻² TDM, with grain filling attributed to sustained P_N (less than 35% reduction during late stages). This resulted in yields of 7.6 t ha⁻¹, compared to only 5.1 t ha⁻¹ in Lalat. By integrating crop residues with N fertilizers (2010–11), Gayatri achieved yields of 5.93 t ha⁻¹, showing how nutrient recycling sustains photosynthetic activity and dry matter partitioning. These examples reinforce that sustained photosynthesis during reproductive stages is critical for maximizing harvest index and yield.

3.11 Photosynthetic Resilience Under Drought, Submergence, and Heat Stress Informing Breeding for Climate-Adaptive Rice Varieties

CRRI's experiments extensively probed how photosynthesis responds to stress environments. Drought tolerance: In 2004–05, varieties like IET 18235 maintained high RWC (71.6%) under 8 bar stress, sustaining photosynthesis and dry matter accumulation. Later, in 2019, black rice lines were identified that combined drought and submergence tolerance, retaining photosynthetic function under stress for up to three weeks. High temperature: In 2006–07, studies revealed that a 19°C increase during grain filling reduced spikelets m⁻² and fertility, particularly in sensitive varieties like Satabdi. This demonstrated the vulnerability of photosynthesis and reproductive success to heat stress. However, micronutrient interventions such as boron application in 2014–15 enhanced filled grain percentage (78%) under high temperature in KB-22. Submergence tolerance: Introduction of the Sub1 QTL into Swarna and other

backgrounds (2011–12) was confirmed to preserve photosynthetic activity under submergence, as revealed by chlorophyll fluorescence OJIP transients. These findings established that maintaining photosynthetic activity under stress is the defining feature of tolerant genotypes and a crucial breeding target.

3.12 Transgenic and C₄ Pathway Engineering Approaches Toward Breaking Yield Barriers Through Enhanced Photosynthetic Capacity

To overcome the intrinsic limitations of the C₃ pathway, CRRI pursued transgenic interventions by introducing C₄ pathway genes and related enzymes into rice. In 2017–18, rice lines were successfully transformed with SiPPDK, SiME, SiPEPC, and SBiC genes, laying the foundation for partial C₄ pathway expression. By 2018–19, transgenic lines expressing the SbCA (carbonic anhydrase) gene showed enzyme activity ranging from 19–47 units μg^{-1} protein, 2–5 times higher than controls (8.9–10.1 units). These plants also exhibited higher photosynthetic rates compared to wild-type IR 64. In 2019, a transgenic plant (No. 26) expressing *Setaria italica* PPDK (SiPPDK) recorded the highest photosynthetic rate among tested lines, with significantly enhanced enzyme activity and improved productivity over controls. In 2023, the introduction of SiPEPC fragments into IR 64 backgrounds increased PEPC enzyme activity by 2.2–6.4 fold compared to controls, with expression levels reaching 9.1-fold higher in some lines.

Recent evaluations of New Generation Rice (NGRs) identified lines with inherently superior photosynthetic capacity. In 2022, genotypes like CR 4336-13-1-1-2, CR 4030-3-3-3-1-1-1, and CR Dhan 328 recorded P_N values of 27.8, 25.3, and 24.2 $\mu\text{mol m}^{-2} \text{s}^{-1}$, respectively. These high rates were positively correlated with seed yield and biomass. Such findings demonstrate that physiological screening for photosynthesis can directly inform breeding pipelines, ensuring that NGRs combine genetic yield potential with physiological efficiency (**Table 8**).

Table 8: Compilation of Physiological Research Outcomes Forming a Knowledge Repository for Trait Discovery, Marker Development, and Accelerating Physiology-Informed Molecular Breeding in Rice

Year	Research Focus	Trait/Mechanism Studied	Key Quantitative Finding/Detail	Related Genotypes/Context	References
2000-01	Phenological Phases	Total Growth Period	Reduced by 28 days in late direct-seeded vs transplanted rice	Found in late direct-seeded conditions	CRRI Annual report 2000-01
2000-01	Plant Physiology	Photo-insensitive variety screening	Higher yield obtained by late sowing	Appropriate sowing date identified for different maturity groups	CRRI Annual report 2000-01
2002-03	Methane Emission	Root Oxidation Activity (ROA)	ROA negatively correlated with methane emission	ROA highest in K39 and Ratna; methane emission lowest in Lalat	CRRI Annual report 2002-03

Year	Research Focus	Trait/Mechanism Studied	Key Quantitative Finding/Detail	Related Genotypes/Context	References
2002-03	Abiotic Stress Tolerance	Anti-oxidative Enzymes (ADH) activity	Effective in tolerance to submergence and higher survival (50%)	FR13A, IR42 (tolerant) vs. Swarna (susceptible)	CRRI Annual report 2002-03
2004-05	Submergence Tolerance	Physiological responses	Chlorophyll fluorescence spectrophotometry to identify sub. tolerant germplasm	Tolerant entries: Sarala, Gayatri, IR 42	CRRI Annual report 2004-05
2006-07	High Temp Stress	Grain filling at high temperature	Temperature increase (19°C) decreased spikelet/m ² and fertility	IR 72, Annapurna, DRRH 1, Satabdi	CRRI Annual report 2006-07
2011-12	Photosynthetic Rate (N levels)	P_N , TDM, Grain yield	Rate increased linearly in hybrids with N level increase (N0 to N200)	Ajay, Rajalaxmi, CRHR32	CRRI Annual report 2011-12
2012-13	Abiotic Stress Tolerance	Marker-Assisted Selection (MAS)	Introgression of grain yield under drought stress QTLs confirmed	IR 64 Sub1 (Context of breeding efforts)	CRRI Annual report 2012-13
2018-19	Genetic Enhancement (Photosynthesis)	Carboxyanhydrase (CA) enzyme activity	Transgenic rice lines (SbCA) showed 2–5 folds higher CA enzyme activity than control	Transgenic lines (SbCA)	CRRI Annual report 2018-19
2019	Drought/Submergence Tolerance	Trait identification	Four black rice lines drought tolerant; three lines showed submergence tolerance up to three weeks	Black rice germplasm lines	CRRI Annual report 2019
2021	Root Morphology (Drought)	Root length density (RLD), Root Volume (RV)	RLD max: 1.96 cm cm ⁻³ (BADAJANGIA); RV max: 13.15 cc (TAGUR)	BADAJANGIA, BEEK JER, TAGUR, SALKAIN	CRRI Annual report 2021

Year	Research Focus	Trait/Mechanism Studied	Key Quantitative Finding/Detail	Related Genotypes/Context	References
2023	Straw Quality	Quantitative Trait Loci (QTL)	Significant Marker-Trait Associations for Dry Matter, Ash, Nitrogen, Lignin, and Cellulose content	Mapping using GLM and MLM approaches	CRRI Annual report 2023

4: Integration of Physiological Research with Breeding Programs for Accelerating Genetic Gains and Varietal Development

4.1 Bridging Physiology with Breeding Through Trait Identification and Donor Selection for Targeted Crop Improvement

The physiological studies on yield, growth indices, and photosynthesis carried out at ICAR-CRRI were not isolated exercises. Instead, they provided a functional bridge between crop physiology and breeding programs. Traits such as high harvest index, stable NAR under stress, higher photosynthetic rates, and efficient dry matter partitioning were identified as marker traits for yield potential and stress resilience. Breeders used these findings to select donors, validate crosses, and pyramid traits in new varieties. For example, the demonstration that hybrids consistently maintained HI above 0.50 and sustained high CGR informed hybrid breeding programs. Similarly, the physiological identification of drought-tolerant landraces with deeper roots and high RWC enabled breeders to introduce such traits into improved lines through marker-assisted selection (MAS).

4.2 Deployment of Sub1 Gene for Submergence Tolerance Demonstrating Successful Translation of Physiological Insights into Flood-Resilient Varieties

One of the landmark integrations was the deployment of the Sub1 gene, conferring submergence tolerance. Physiological studies had shown that tolerant genotypes-maintained chlorophyll fluorescence, green leaf area, and survival rates under flooding. Translating this into breeding, CRRI introduced Sub1 into popular cultivars like Swarna and developed lines such as CR Dhan 806 (Varshadhan Sub1). These varieties-maintained productivity in flood-prone lowlands, demonstrating the direct application of physiological insights into breeding pipelines.

4.3 QTL Mapping and Marker-Assisted Selection Enabling Precision Introgression of Physiological Traits into Elite Backgrounds

CRRI made extensive use of quantitative trait loci (QTL) mapping to link physiology with genetics. QTLs for drought tolerance were identified and validated using physiological markers such as spikelet fertility under heat stress, root anatomical traits, and RWC. MAS was used to pyramid resistance genes for

bacterial blight, blast, and drought tolerance while ensuring that physiological traits such as photosynthetic efficiency and HI were retained. In 2023, QTLs associated with straw quality traits (dry matter, Nitrogen, lignin, cellulose) were mapped, reflecting the broadening scope of physiological breeding beyond yield to include residue management and nutritional quality. This integration demonstrates that physiology-informed QTLs accelerate breeding by combining agronomic performance with molecular precision.

4.4 Genome Editing and CRISPR Applications

The most recent frontier has been the application of CRISPR/Cas9 genome editing to target specific genes related to physiology and yield. Genes like IPA1, EPFL9, Gn1a, and SD1—all associated with plant architecture, panicle size, and biomass partitioning were targeted for precise edits. Physiological studies had shown that traits such as larger sink size, optimized plant height, and enhanced photosynthetic enzymes strongly correlated with yield. CRISPR editing allowed breeders to directly modify these genes while retaining desirable physiological traits. This convergence of genome editing with physiology marks a paradigm shift: rice improvement is no longer limited to selection and crossing but can now precisely engineer photosynthetic and growth efficiency traits.

4.5 Transgenics and Synthetic Biology Approaches

CRRI's pioneering work on introducing C₄ pathway genes into rice is a major step toward reprogramming photosynthesis. Genes such as SiPPDK, SiPEPC, SiME, and SbCA were introduced to increase CO₂ concentration at the site of Rubisco, thereby enhancing carboxylation efficiency. While these transgenics are still experimental, they highlight the synthetic biology approach to physiology: rather than depending on natural variation alone, researchers are actively building new metabolic pathways into rice to break yield barriers.

4.6 Farmer-Level Demonstrations and Participatory Breeding

Breeding efforts were consistently validated in farmer participatory trials, ensuring that physiological improvements translated into field-level adoption. Varieties like CR Dhan 307 (2017–18) and CR Dhan 314 (2023) were tested across farmer fields, showing 30–36% yield advantages over local checks. This participatory approach ensured that traits such as higher tiller density, more grains per panicle, and resilience to stress were not just physiological curiosities but practical advantages valued by farmers. By bridging physiology with farmer validation, CRRI demonstrated the applied impact of integrating research with extension models like INSPIRE.

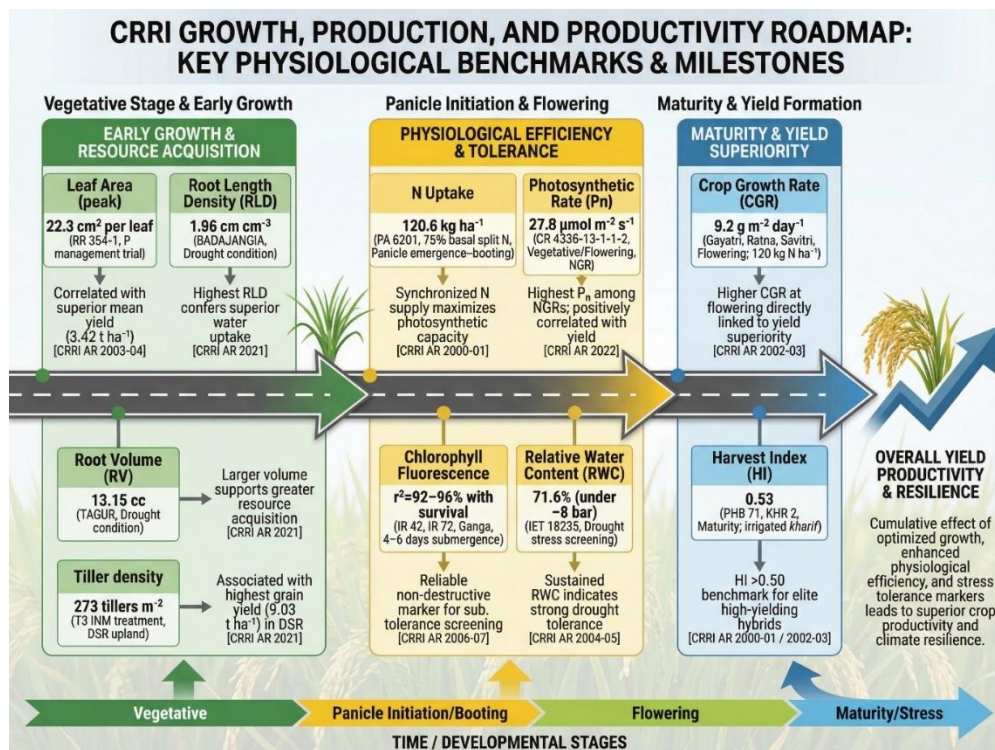


Fig. 3: Integrated Research Roadmap Linking Physiology, Breeding, and Productivity to Provide a Strategic Framework for Prioritizing Future Research Directions and Translating Physiological Insights into Climate-Resilient Varieties

5: Future Approaches for Advancing Rice Productivity Through Convergence of Physiology, Molecular Biology, and Precision Agronomy

The next frontier in enhancing rice productivity lies in integrating physiological insights with modern molecular tools, precision agronomy, and climate-resilient strategies. Research from ICAR-CRRI has laid a strong foundation by dissecting growth indices such as Crop Growth Rate (CGR), Net Assimilation Rate (NAR), and Harvest Index (HI), and linking them to yield. Moving forward, the challenge is to build upon this physiological knowledge using innovative approaches that can overcome the inherent limitations of rice as a C₃ crop, while addressing emerging challenges posed by climate change, resource constraints, and food security demands.

One promising direction is the engineering of photosynthesis. Efforts to introduce C₄ pathway genes (PEPC, PPDK, CA, ME) into rice have shown that partial expression of C₄ enzymes can significantly increase carboxylation efficiency and reduce photorespiratory losses. Coupled with synthetic biology approaches, such transformations aim to create "super rice" capable of sustaining higher photosynthetic

rates under both optimal and stress conditions. Similarly, the use of transgenic lines with enhanced carbonic anhydrase activity and improved mesophyll conductance opens avenues for higher radiation use efficiency and biomass accumulation.

Equally critical is the deployment of genome editing tools, especially CRISPR/Cas9. Recent breakthroughs allow precise modification of key genes such as IPA1 (tillering and panicle branching), Gn1a (grain number), and EPFL9 (stomatal density regulation), directly translating physiological traits into genetic gains. Such precision breeding is expected to shorten varietal development cycles and ensure that desirable physiological attributes such as high HI, stable NAR, and superior root traits are directly introgressed into high-yielding backgrounds. Precision nutrient management forms another pillar of future productivity enhancement. Tools like GreenSeeker, SPAD-based monitoring, and Leaf Colour Charts (LCCs), combined with nano-fertilizers, enable synchronization of nutrient supply with crop demand. These eco-friendly innovations not only increase nitrogen-use efficiency but also minimize environmental footprints, addressing sustainability concerns. Moreover, integrating organic and inorganic sources through site-specific nutrient management ensures that rice cultivation adapts to diverse ecologies without yield penalties.

Climate resilience must also remain a central focus. Physiological studies have revealed how traits such as high relative water content (RWC), efficient dry matter partitioning, and sustained photosynthetic rates under stress confer tolerance to drought, submergence, and high temperatures. Breeding programs must integrate these insights with QTL mapping, marker-assisted selection, and genomic prediction models. The Sub1 introgression success demonstrates the power of physiology-guided breeding; similar pipelines for heat- and drought-resilient traits hold immense promise. At the systems level, direct-seeded rice (DSR), integrated crop-livestock systems, and conservation agriculture offer sustainable pathways to reduce water use, methane emissions, and production costs. Coupled with farmer-participatory breeding and extension models like INSPIRE, these approaches ensure that research outputs translate effectively into farmer adoption.

In summary, the future of rice research is likely to be shaped by a convergence of advanced molecular biology, physiological screening, and smart agronomy. By combining traditional breeding wisdom with cutting-edge biotechnological and precision tools, it is possible to develop rice varieties that are not only high yielding but also climate-resilient, resource-efficient, and environmentally sustainable.

6: Conclusion

Rice productivity enhancement over the past two decades at ICAR-CRRI has underscored the importance of integrating physiology with breeding and management. Detailed studies on photosynthesis, growth indices, and nutrient use efficiency have clarified how traits such as high HI, stable NAR under stress, optimal LAI, and efficient partitioning drive yield stability across diverse ecologies. Simultaneously, innovations like SRI modifications, precision nitrogen management, and submergence-tolerant Sub1 varieties have shown that physiology-based interventions can be directly translated into tangible yield gains at the farmer's level.

The modern phase of rice research is now marked by transformative approaches including genome editing, C₄ pathway gene introgression, transgenic enhancements, and the deployment of nano-fertilizers and precision tools. These strategies, combined with physiological markers, provide unparalleled opportunities to break yield barriers while ensuring resilience under climate change. At the same time, systems-based innovations like DSR and integrated farming enhance sustainability and resource use efficiency. Going forward, the challenge will be to harmonize these approaches *i.e.*, molecular, physiological, and agronomic—into a coherent pipeline that addresses farmer needs and environmental sustainability. With continued investment in physiology-driven breeding and farmer-participatory validation, rice improvement programs can meet the dual goals of ensuring food security and ecological balance. Thus, the journey from understanding plant physiology to deploying modern technologies promises a resilient, productive, and sustainable rice sector for the future.

7: References

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