Policy Paper 54

Economic Evaluation of Climate-Resilient Rice Varieties

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Preface

Rice is the primary staple food in India, both in terms of production and consumption. However, the increasing frequency and severity of climate-induced stresses, such as droughts, floods, and salinity, pose significant threats to the stability and productivity of rice production systems. Smallholder farmers, who comprise a significant portion of the farming population, encounter challenges in addressing these shocks due to their limited resources and adaptive capacity. Traditional mitigation practices, such as irrigation and drainage, are insufficient and costly. Furthermore, their declining effectiveness over time is a concern.

Climate-resilient crop varieties represent a promising approach to enhancing farmers' adaptive capacity by offering inherent tolerance to multiple stresses without incurring additional financial costs. These stress-tolerant varieties serve as a form of insurance, ensuring yield stability and improving productivity under adverse climatic conditions. In recent years, the National Agricultural Research System has released over 2,600 varieties of various crops, including rice, that exhibit tolerance to different types of stress. The 21 climate-resilient rice varieties evaluated in this study demonstrate both productivity and risk mitigation benefits against different climate stresses. Breeding climate-resilient varieties is a cost-effective adaptation measure that can be easily propagated and distributed.

The evidence presented in this paper is intended to guide research administrators, researchers, and policy makers in addressing climate change by developing and distributing climate-resilient rice varieties.

Pratap Singh Birthal
Director, ICAR-NIAP

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Authors

Contents

List of Tables

List of Figures

Executive Summary

Climate change poses a serious threat to the capacity of the food system to continuously feed and farmer livelihoods in South-East Asia as well as in India. Extreme climatic events like droughts, floods, heat stress coupled with erratic monsoon pattern not only destabilize the crop yields but also reduce their mean yield. Rice is key to the dietary preferences and food security of million people in this region. Evidences suggest that without adaptation, the mean yield in rainfed and irrigated rice ecologies in India could decline by around 20% and 3.5%, respectively by 2050. This decline would not only undermine the household food security & farm income, but could potentially weaken the human-land linkage which has severe consequences. This impact falls hardest on small and marginal farmers, who make up over 86% of India's farmers and cultivate about 47% of its cultivable land. With a small operational landholding, these farmers have limited adaptive capacity to mitigate the impacts of crop failure due to climatic shocks, leaving them highly exposed.

National Innovations in Climate Resilient Agriculture (NICRA) has identified about 310 districts (40%) as the most vulnerable (109 districts (14%) as 'Very High' and 201 districts (26%) as 'Highly' vulnerable category) to climate change. About 68% of the net sown area (NSA) is reported to be vulnerable to drought of which 50% are classified as severe, where drought is almost a regular phenomenon. Contrarily, approximately 33% of the cultivable area is flood-prone in India. Moreover, in all the regions there are districts which are prone to heat stress.

These instigated the resilience strengthening efforts, both at the central and state levels. Irrigation has traditionally proven a reliable strategy to counteract drought-induced yield losses in rice cultivation. However, the efficacy of irrigation as a mitigation strategy has declined, likely due to the intensifying effects of climate change on water availability. Contrarily, the farm drainage was sought as an agronomic intervention for managing the effect of flood. However, as recently witnessed in Punjab, the intensity and the spread of flood limits the farmer's ability to manage it. In view of this, improving stress-tolerance of crops through genetic improvement is identified as a promising strategy to mitigate effects of climate change. The resilience trait embedded in seed acts as an insurance and is claimed to be a cost-effective means of mitigating effects of climate change. In India, the national agricultural research system has made significant strides in developing rice varieties with purported resistance to multiple environmental stressors. These are claimed to be a cost-effective and relatively straightforward approach to enhancing crop resilience. So far, National Agricultural Research System (NARS) has released over 2,600 climate-resilient crop varieties.

However, there remains a gap in our understanding of the economic and social impacts of such stress tolerant varieties. Several studies have evaluated the impact of varietal development, focusing primarily on productivity enhancements. Nevertheless, yield-based estimates overlook the stabilizing effects of resilience traits embedded in the resilient varieties. This study aims to fill this gap by evaluating the benefits of both yield-enhancing and risk-reducing traits of the crop varietal technology.

Key findings

Currently, about 10% of the total rice acreage is cultivated with nearly one hundred climate-resilient rice varieties. This study includes 21 (around 10-15%) of these climate-resilient varieties (CRVs) (classified into drought tolerant, submergence tolerant, drought & submergence tolerant, salinity tolerant, aerobic and biotic stress tolerant) cultivating on approximate 3.82 million hectare area (7.9% of total rice area). Among the CRVs, widespread and regular incidences of drought and flooding events led to wider adoption of drought- and submergence-tolerant varieties—notably *Sahabhagi Dhan* and *Swarna Sub-1*, each covering 1.66 million hectares (3.5% of total rice area). Nevertheless, other promising varietal groups—such as dual-tolerant (drought- and submergence-tolerant), salinity-tolerant, and aerobic rice varieties—have also been adopted, though over relatively smaller areas. Their limited spread reflects the localized nature of stresses, seed supply constraints, uneven extension outreach, and the presence of alternative livelihood options in these regions. Biotic stress-tolerant varieties included in the study are relatively recent introductions, and consequently their current area expansion remains limited.

Estimates suggest that, at the current adoption pace, by the year 2030, the climate resilient rice varieties would generate an economic surplus of Rs. 2,11,034 crore for the society due to their mean yield benefits which is equivalent to Rs. 10774 crore per annum (4.89% of gross value of output of paddy at 2011-12 price for the year 2022-23).

In addition to the productivity gains due to mean yield effect, the resilient traits embedded in the CRVs offers risk-reduction benefits to the farmers through yield stabilization effects. The total risk-reduction benefit of Rs. 10,672 crore highlights the stabilizing role of CRVs, especially for smallholder farmers whose livelihoods are most vulnerable to production shocks.

At the farm level the total economic benefits range from Rs. 17540.40 to Rs. 47160.51 per hectare due to adoption of different groups of CRVs. This benefit is inclusive of mean yield effect during the normal period and downside risk-reduction during the stress conditions which disproportionately affect smallholders. Such seeds with embedded traits against different abiotic and biotic stresses, not only improves economic resilience of the farmers, but also the yield resilience of the production system.

Despite, substantial economic benefits from the CRVs adoption as evident from this study, there exist scope for targeting diverse abiotic and biotic stresses, enhancing adoption of these cultivars for risk proofing and integrating CRVs in the regional agricultural contingency planning. The study suggests to-

- *Strengthen climate-resilient crop improvement systems:* Prioritise breeding pipelines that integrate both productivity-enhancing and risk-mitigating traits, supported by coordinated research platforms, predictable funding, and streamlined varietal release pathways. Additionally, private sectors participation in development and dissemination of such varieties across crops may be encouraged.
- *Build a responsive and region-specific seed delivery ecosystem:* Enhance breeder and foundation seed production, establish decentralised seed hubs in vulnerable districts, and ensure timely supply of improved varieties through national and state seed programmes. FPOs and farmer's groups may be encouraged to take up agri-entrepreneurship in seed production/multiplication and supply at the grass root level.
- *Integrate climate considerations into agricultural planning and risk-management frameworks:* Align district contingency plans, disaster-response protocols, and crop insurance mechanisms with evidence-based varietal and agronomic recommendations that minimise yield losses under stress. Insurance companies may take into cognizance of risk reduction technologies adopted by the farmers while deciding the individual premium. Additionally, the aggressive effort may be put on place to deploy such risk reduction technologies at farm level in the vulnerable regions.
- *Improve extension systems to support adaptive decision-making:* Expand multi-year demonstrations, strengthen KVK-led advisories, and deploy digital tools to provide farmers with location-specific guidance on varieties, agronomy, and climate-related risks. The proactive measures may be taken to encourage the visibility of such low cost and risk

reduction technologies in the targeted regions for rapid take up of these technologies.

- *Prioritise investments and incentives for high-risk geographies and vulnerable farmer groups:* Target public resources, input support, and institutional services to regions with recurrent climatic stresses and to communities with limited adaptive capacity, ensuring equitable uptake of improved technologies and practices.

1 Introduction

The integration of advanced technology into the agricultural sector is no longer an optional growth strategy but a national imperative driven by the urgent threats posed by climate change, resource scarcity, and the socioeconomic demands of a vast smallholder population. Climate change is already altering the frequency, patterns and severity of extreme weather events—droughts, floods, heat waves and erratic monsoons—that directly threaten agricultural productivity and rural livelihoods across South Asia. The Intergovernmental Panel on Climate Change (IPCC) finds that climate variability and extremes are intensifying and the agro-ecosystems in South and Southeast Asia are especially vulnerable given their dependence on monsoonal rainfall and seasonal cropping patterns (IPCC, 2022). These stresses translate into measurable yield penalties and intensified yield variability for staple cereals (Birthal et al., 2014), with rice being particularly exposed in both irrigated and rainfed ecologies (Palanisami et al., 2017; Singh et al., 2024).

Rice is central to India's food security and rural economy. It remains the primary staple for a large segment of the population and occupies one of the largest cropped areas nationally (22.77% of gross cropped area), accounting for a substantial share of caloric intake, employment (>40%), and public procurement (>65% of total cereal procurement). Any sustained instability in rice production therefore has immediate implications for household food security, poverty, market prices and macroeconomic stability. Recent assessments also indicate that climate-driven yield shocks in major rice-growing regions can propagate into inflationary pressures and distributional harms that disproportionately affect vulnerable households (IPCC, 2022; Santhosh et al., 2024).

Conventional adaptation options—such as irrigation expansion, infrastructure investments, insurance and altered agronomic management—are essential but often costly, slow to implement, or unevenly accessible to resource-poor smallholders (Birthal, 2022). In this context, climate-resilient crop varieties (CRVs) have emerged as a complementary, scalable, and farmer-centric adaptation strategy. CRVs are bred for tolerance to abiotic stresses (drought, submergence, salinity, heat, etc.) and biotic stresses; they can deliver two interlinked benefits: a positive mean yield effect under normal conditions and a reduction in downside losses during climatic shocks. Empirical evaluations have documented yield gains for stress-tolerant rice varieties (STRVs) relative to local checks—often in the order of several hundred kilograms to nearly a tonne per hectare in stress-prone environments—and meaningful improvements in stability and household welfare in affected regions (ICRISAT, n.d.; Bairagi et al., 2021).

Despite these demonstrated agronomic advantages, the economic valuation of CRVs—particularly the separate monetization of mean yield enhancement and risk-reduction/stability benefits—remains fragmented. Most impact assessments emphasized average yield differentials or adoption rates, but fewer studies systematically translated stability gains into monetary terms. This evidentiary gap is consequential: policymakers and donors require credible, transparent valuations to prioritise investments, design seed-supply interventions, and calibrate incentives (e.g., subsidies, breeder-seed indents, insurance modulations). Without rigorous monetization of stability benefits, the public value proposition of CRVs—especially their role in mitigating income losses—may be undervalued in policy deliberations.

Moreover, adoption of CRVs has been heterogeneous and, in many contexts, slower than expected, even where trials indicate agronomic superiority. Reasons include limited seed availability, delays in seed multiplication, mismatches between varietal quality attributes and local consumer preferences, weak extension and demonstration coverage, risk-averse farmer behaviour, and competing institutional priorities (Patil and Veettil., 2024; Jena et al., 2023). Understanding the economic returns from both the mean-yield and the stability is therefore essential to design policies that translate breeding gains into large-scale welfare improvements.

This study addresses these needs by estimating the economic benefits of climate-resilient rice varieties. Using credible multi-location yield trial data, augmented with adoption statistics, the paper quantifies (a) adoption behaviour of six groups of climate resilient rice varieties, (b) the macro and micro level economic value of yield enhancing and (c) yield stabilisation attributes in the resilient varieties.

The rationale for this investigation rests on three policy imperatives. First, quantifying the economic value of resilience—including its insurance-like role in preventing downside losses—improves the targeting and cost-effectiveness of public investments in varietal development and seed systems. Second, monetized evidence on stability benefits which permits direct comparisons between CRVs and alternative mitigation strategies (e.g., irrigation, insurance, infrastructure), thereby enabling better allocation of scarce public funds. Third, credible valuation strengthens the case for institutional support (seed multiplication, market linkages, extension) and for designing incentives that accelerate adoption among smallholders who are typically risk-averse and liquidity-constrained. By making explicit the combined farm-level and system-level economic returns from resilient traits, this study aims to provide the evidence base necessary for policy advocacy, institutional scaling, and strategic investment in climate-smart varietal technologies.

2 Climate Change and Climate-Resilient Agriculture

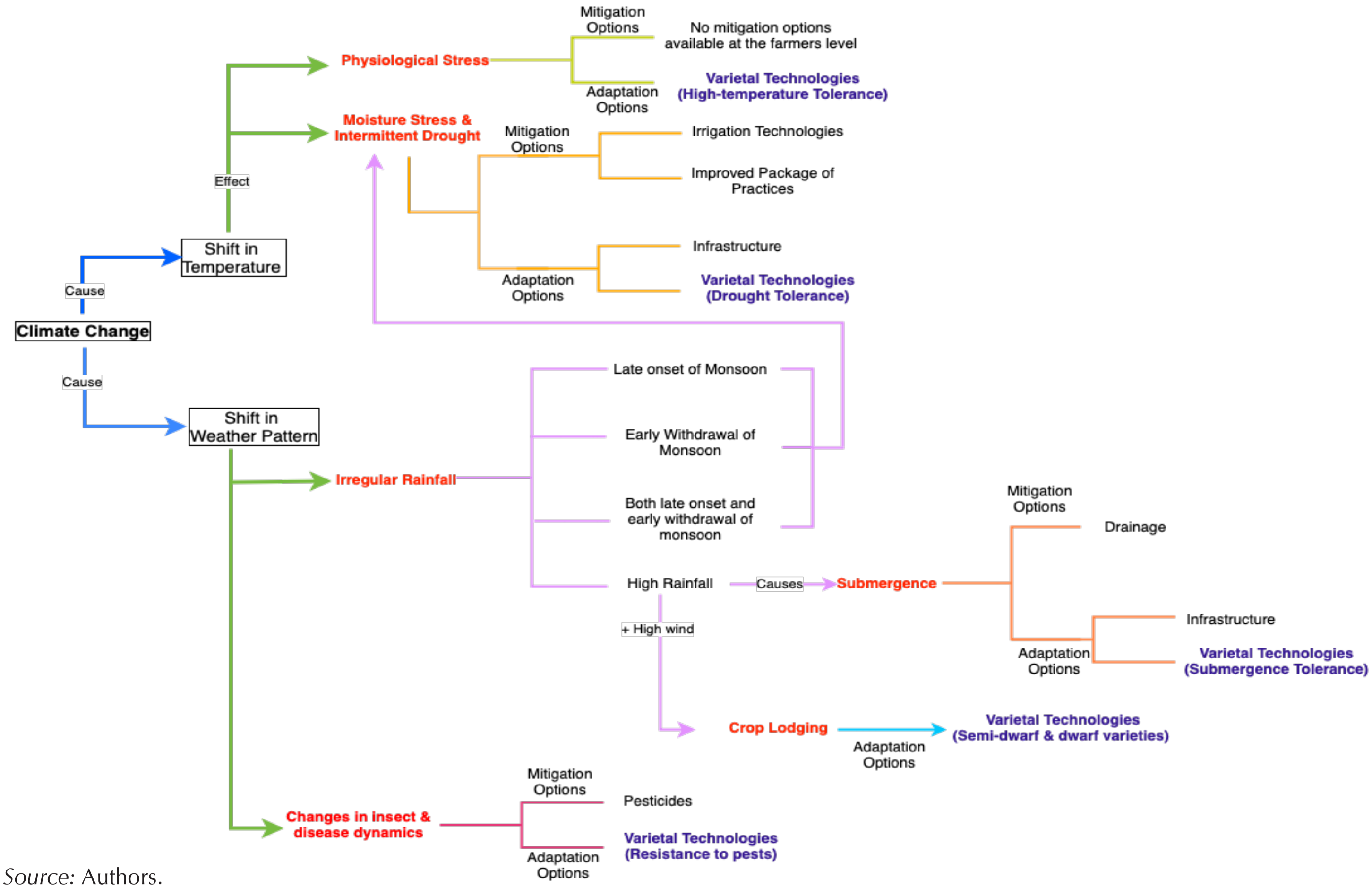
The United Nations (UN) defines climate change as "long-term shifts in temperatures and weather patterns". This refers to persistent deviations in temperature, precipitation, and other climatic parameters from their normal levels. Such changes gradually alter agro-ecological systems and farming practices. The recent episodes of flooding in Punjab and hilly states which affected soil conditions in farmers' fields and changed the field topography, illustrate these impacts.

Rice cultivation in India—one of the climate-sensitive agricultural systems—faces multiple stresses arising from rising temperatures and increasingly erratic weather patterns. Elevated temperatures, driven by greenhouse gas accumulation and long-term climatic transitions, intensify evapotranspiration, reduce soil moisture, and increase the frequency of intermittent drought. These thermal anomalies also impose physiological stress on rice plants, diminishing growth and yield potential (Figure 1).

Adaptation to temperature-induced stress requires a combination of genetic, agronomic, and water-management innovations. Heat-tolerant rice offers a direct genetic response to elevated temperatures. Agronomic practices including direct seeded rice (DSR) and alternative wetting and drying (AWD) enhance water-use efficiency and mitigate moisture stress. Complementing these biological and management measures, strengthened irrigation infrastructure—such as canal networks, farm ponds, water reservoirs, and micro-irrigation systems—plays a critical role in improving water availability and reducing vulnerability to drought.

Shifts in precipitation patterns present an additional set of risks. Irregular rainfall—including delayed monsoon onset, premature withdrawal, and intra-seasonal variability—exacerbates soil moisture deficits and disrupts crop calendars. Conversely, excessive rainfall, especially when accompanied by high-velocity winds, can lead to waterlogging and submergence of standing crops, causing significant yield losses as observed in case of Kharif rice crop this year which exacerbates income insecurity.

Figure 1. Climate change, its impacts, and adaptation options for Indian rice farmers



Source: Authors.

These risks can be mitigated through land levelling, improved field drainage, and the adoption of submergence-tolerant rice varieties that help maintain productivity under inundated conditions. High wind events also increase the incidence of lodging, the severity of which varies with crop stage and varietal traits; dwarf and semi-dwarf varieties provide structural stability and reduce lodging susceptibility.

Climate change further influences pest and disease dynamics by altering the ecological conditions that regulate their prevalence and virulence. While pesticides offer short-term mitigation, the breeding and deployment of rice varieties with genetic resistance to major pests and diseases constitute a more sustainable and environmentally sound long-term response.

2.1 Climate-resilient agriculture

Climate-resilient agriculture (CRA) is a comprehensive approach that integrates adaptation, mitigation, and sustainable resource management to strengthen farming systems against climate-related shocks. It enhances the capacity of agriculture to anticipate, absorb, recover from, and adapt to climate impacts, thereby maintaining productivity, ecological balance, and livelihoods of dependent. CRA not only aims to reduce vulnerability to these disturbances but also ensures that agricultural systems retain its core functions and recover effectively.

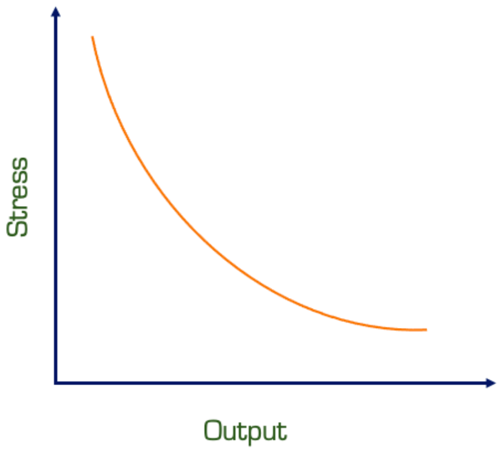
Resilience in agriculture spans ecological, technological, and socio-economic dimensions. It requires proactive planning, risk assessment, and efficient use of land, water, soil, and genetic resources, alongside improved access to innovations, climate services, and decision-support tools. CRA is defined by three key attributes:

1. Resistance – Minimizing damage during climate shocks,
2. Recovery – Rapid restoration of core function, and
3. Transformation – Long-term adaptation through systemic changes in practices and technologies.

In practice, CRA promotes stress-tolerant crop varieties, climate-smart practices, biodiversity conservation, and adaptive infrastructure. The Capability Approach (Sen) reinforces the need to empower farmers with the tools and freedoms to respond effectively to climate risks. According to the IPCC (2021), resilience-focused interventions are vital for ensuring food security, reducing poverty, and sustaining agricultural systems under changing climate conditions. CRA thus serves as both an adaptation strategy and a foundation for long-term sustainable development.

2.2 Climate-resilient crop variety

Figure 2. Relationship between the crop output and the degree of stress



Crop output is shaped by multiple abiotic (e.g., drought, heat, salinity) and biotic (e.g., pests, diseases) stresses. Generally, greater stress reduces yields (Figure 2), but the impact depends on the frequency, intensity, timing, and type of stress, as well as the crop's stage of growth and its inherent tolerance.

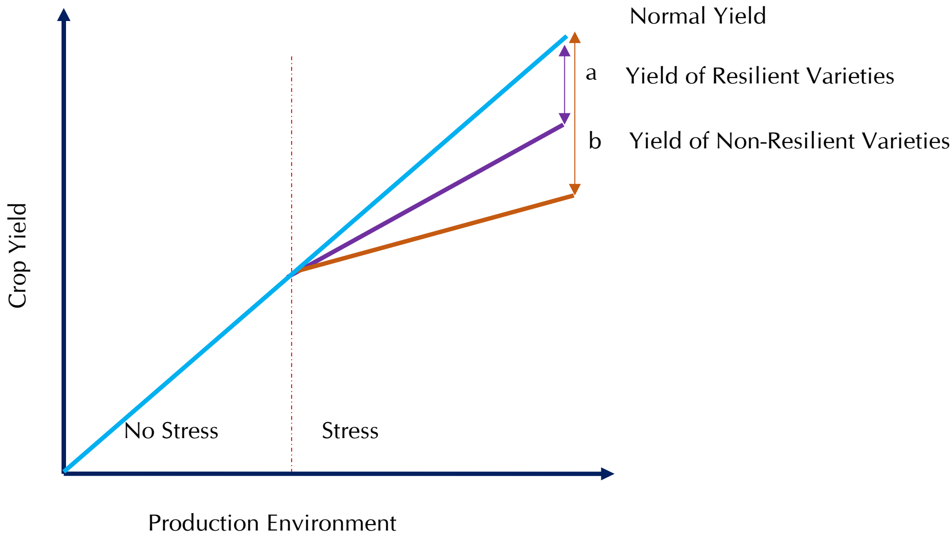
Stress during sensitive phases—like flowering—can cause severe yield loss, even if brief. Different stress types elicit distinct crop responses, and varieties differ in their ability to resist or recover. Abiotic stresses typically limit resources, while biotic ones trigger defensive mechanisms. Thus, crop productivity under stress reflects a complex interaction of environmental conditions and biological responses. Understanding these factors is essential for developing climate-resilient crops and adaptive farming practices.

The escalating challenges posed by climate change led to significant advancements in plant breeding, which have enabled the development of crop varieties capable of responding effectively to a range of biotic and abiotic stresses. These climate-resilient or climate-smart varieties are not immune to yield reductions under stress; rather, their key advantage lies in their reduced sensitivity to adverse conditions, resulting in relatively smaller deviations from average (mean) yields. Resilience, therefore, should not be misconstrued as absolute resistance or the ability to maintain normal yields under all circumstances, but instead as the crop's relative capacity to minimize yield loss when subjected to stress.

This stability is conferred by specific physiological and genetic traits that enhance tolerance to drought, heat, submergence, salinity, pests, and diseases. Such traits are the result of advanced breeding methodologies—such as marker-assisted selection, genomic selection, and genetic engineering—which allow for targeted improvement aligned with specific agro-climatic challenges.

Figure 3 illustrates this concept of yield stability under stress. Under optimal conditions, both resilient and non-resilient varieties perform similarly, with comparable yield levels. However, under stress scenarios, yields decline in both cases. The resilient variety, due to its adaptive traits, shows a smaller yield reduction—denoted as deviation "a" from the mean yield—compared to the larger reduction "b" observed in the non-resilient variety. The difference in these deviations (b – a) represents the avoidable yield loss that a farmer could potentially prevent by adopting a resilient variety.

Figure 3. Yield deviation of climate-resilient and non-resilient rice varieties from the mean under stress conditions

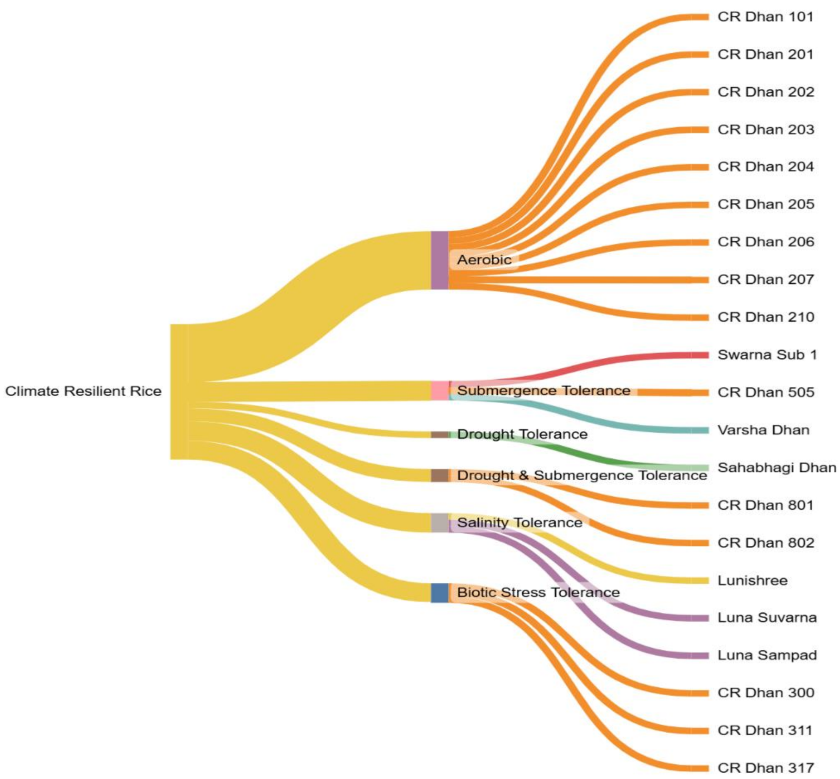


In this context, climate-resilient crop varieties play a vital role in stabilizing agricultural productivity, reducing climate-induced risks, and ensuring more consistent returns for farmers. Their development and dissemination are central to building climate-resilient agricultural systems and supporting adaptation at the farm level. This study has considered such climate-resilient non-basmati rice varieties for their impact evaluation.

2.3 Features of selected climate-resilient varietal technologies

For this study, we selected 21 non-basmati rice varieties exhibiting six different climate-resilient traits. The climate-resilient features of the selected varietal technologies include aerobic, submergence, drought, drought and submergence tolerance, salinity tolerance, and biotic stress tolerance (Figure 4).

Figure 4. Selected rice varieties with different climate-resilient traits



2.3.1 Aerobic varieties

Aerobic varieties represent an environmentally sustainable innovation in rice cultivation, particularly suited for regions facing acute water scarcity. In contrast to traditional flooded paddy systems, aerobic rice varieties are specifically developed to perform well under non-puddled, well-drained, and aerated soil conditions, thereby substantially reducing irrigation demand. These varieties exhibit enhanced tolerance to drought, pests, and diseases, making them ideal for upland and water-saving agro-ecologies. Notably, aerobic rice systems can reduce water use by up to 50% (Priyanka et al., 2012) and significantly curb methane emissions, offering dual benefits of resource conservation and climate change mitigation. Table 1 outlines the key characteristics of the aerobic rice varieties evaluated in this study.

Table 1. Features of aerobic rice varieties

Variety	Release year	Yield (t/ha)*	Grain type	Maturity duration (Days)	Suitable ecology	Adoption domain
CR Dhan 101	2014	3.98	MS	110	Upland	Odisha
CR Dhan 201	2014	3.80 to 4.00	LS	118	Upland	Bihar and Chhattisgarh
CR Dhan 202	2014	3.70 to 4.50	LB	115	Upland	Jharkhand and Odisha
CR Dhan 203	2014	4.05	LS	110	Upland	Odisha
CR Dhan 204	2014	4.80 to 5.60	LB	120	Upland	Jharkhand and Tamil Nadu
CR Dhan 205	2014	3.70 to 4.50	SB	110	Upland	Gujarat, Madhya Pradesh, Odisha, Punjab and Tamil Nadu
CR Dhan 206	2014	3.95	SB	115	Upland	Odisha
CR Dhan 207	2018	3.70	MS	110-115	Upland	Odisha
CR Dhan 209	2018	4.07	LS	112-115	Upland	Odisha
CR Dhan 210	2020	7.80	LS	110-115	Upland	Odisha

Note: MS: Medium slender, LB: Long bold, LS: Long slender and SB: Short bold; *Yield as per AICRIP trails.

2.3.2 Submergence tolerant varieties

Submergence-tolerant rice varieties, such as *Swarna-Sub1*, *CR Dhan 505* and *Varsha Dhan* represent a significant advancement in climate-resilient agriculture for flood-prone regions like Bihar, Assam, and Odisha. These varieties can survive complete submergence for up to two weeks, stabilizing yields under recurrent monsoon flooding.

Scientifically, these varieties exemplify the integration of traditional breeding with modern biotechnology, particularly through the incorporation of the Sub1A gene, offering a model for future climate-smart innovations. Yield losses with *Swarna Sub1* remain below 20% when flooding occurs after crop establishment, compared to 40–50% if flooding happens immediately post-transplanting (Singh et al., 2009). Field trials show yield advantages of 4–42% over local varieties across diverse locations (Chattopadhyay et al., 2016).

Economically, submergence-tolerant rice enhances income stability for smallholders and supports poverty reduction in vulnerable areas. Their widespread adoption contributes to both environmental resilience and social equity. Table 2 summarizes the traits of submergence-tolerant rice varieties included in this study.

Table 2. Features of submergence tolerant rice varieties

Variety	Release year	Yield (t/ha)*	Grain type	Maturity duration (Days)	Suitable ecology	Adoption domain
Swarna Sub 1	2009	5.2	MS	145	Flood prone shallow low land	Odisha
CR Dhan 505	2014	4.5	MS	162	Deep water conditions	Assam and Odisha
Varsha Dhan	2006	3.5 to 4.0	LB	160	Semi-deep water conditions	Odisha

Note: MS: Medium slender, LB: Long bold; *Yield as per AICRIP trails.

2.3.3 Drought tolerant variety

Drought-tolerant rice varieties are a key innovation for addressing climate-induced water scarcity and promoting sustainable agriculture even under water stress. Varieties such as *Sahbhagi Dhan* (India), *Sukha Dhan* (Nepal), and *BR Dhan 56* (Bangladesh) are specifically bred to sustain yields under limited water conditions. In India, *Sahbhagi Dhan* has shown a yield advantage of 0.8 to 1.6 tons per hectare over traditional varieties during droughts. Notably, during the severe 2012 drought, it outperformed local checks by over one ton per hectare, demonstrating its resilience (Dar et al., 2020). Yield gains vary across studies and locations, but consistently highlight its superior performance under moisture stress. Table 3 summarises the features of drought-tolerant rice varieties included in this study.

Table 3. Features of drought-tolerant rice variety

Variety	Release year	Yield (t/ha)*	Grain type	Maturity duration (Days)	Suitable ecology	Adoption domain
Sahbhagi Dhan	2009	3.5 to 4	LB	105	Rainfed upland/ drought prone	Jharkhand and Odisha

Note: LB: Long bold; *Yield as per AICRIP trails.

2.3.4 Drought and submergence tolerant varieties

CR Dhan 801 and 802 offer resilience to multiple climatic stresses. Developed via marker-assisted backcross breeding, they incorporate the *Sub1* gene for submergence tolerance and drought-tolerance quantitative trait loci (QTLs) (*qDTY1.1, qDTY2.1, qDTY3.1*) into the high-yielding *Swarna* background (Pradhan et al., 2019). This dual tolerance ensures yield stability under both flooding and drought conditions. Economically, these varieties lower the yield variability under drought and submergence conditions thereby, stabilizing crop output and support income security for farmers. Table 4 presents key features of the varieties studied.

Table 4. Features of drought and submergence tolerance rice varieties

Variety	Release year	Yield (t/ha)*	Grain type	Maturity duration (Days)	Suitable ecology	Adoption domain
CR Dhan 801	2019	6.3 (NC) 4.0 (SC) 2.9 (DC)	SB	140	Rainfed shallow low land	Andhra Pradesh, Assam, Odisha, Telangana, Uttar Pradesh and West Bengal
CR Dhan 802	2019	6.5 (NC) 4.3 (SC) 2.3 (DC)	SB	142	Shallow low land	Assam, Bihar and Madhya Pradesh

Note: NC: Normal conditions; SC: Submerged conditions; DC: Drought conditions, and SB: Short bold; *Yield as per AICRIP trails.

2.3.5 Salinity tolerant varieties

Salinity-tolerant rice varieties are vital for improving productivity in coastal and salt-affected regions of India, where conventional rice cultivation is constrained by high soil salinity. Varieties such as *Luni Shree*, *Luna Suvarna*, and *Luna Sampad* are bred to perform well in saline and sodic soils, offering yield stability in vulnerable areas. Developed through advanced breeding techniques, they withstand osmotic stress, ion toxicity, and water imbalance associated with saline environments. These varieties enable cultivation on previously unproductive lands, boosting output and reducing reliance on costly reclamation efforts. Table 5 outlines the key features of the salinity-tolerant varieties examined.

Table 5. Features of salinity tolerant rice varieties

Variety	Release year	Yield (t/ha)*	Grain type	Maturity duration (Days)	Suitable ecology	Adoption domain
Luni Shree	1992	4.75	LS	145	Coastal saline conditions	Odisha
Luna Sampad	2010	3.60 to 4.20	SB	140		
Luna Suvarna	2010	3.50 to 4.00	MS	140		

Note: MS: Medium slender, LS: Long slender and SB: Short bold; *Yield as per AICRIP trails.

2.3.6 Biotic stress tolerant varieties

Biotic stress-tolerant rice varieties play a crucial role in protecting crop yields from pests and diseases that severely constrain rice production. Varieties such as *CR Dhan 300*, *CR Dhan 311*, and *CR Dhan 317* have been developed with genetic resistance to key biotic stresses, including bacterial blight, blast, and brown plant hopper.

Table 6. Features of biotic stress-tolerant rice varieties

Variety	Release year	Yield (t/ha)*	Grain type	Maturity duration (Days)	Suitable ecology	Adoption domain	Stress tolerant features
CR Dhan 300	2013	5.00 to 5.50	LS	140	Irrigated conditions	Bihar, Gujarat, Maharashtra and Odisha	Resistant to leaf folder and moderately resistant to leaf blast, neck blast, sheath rot and sheath blight
CR Dhan 311	2019	5.54	LB	120-126	Irrigated conditions	Assam and Odisha	Tolerant to leaf blast, brown spot, tungro virus, bacterial leaf blight and moderately resistant to gall midge and stem borer
CR Dhan 317	2021	4.58 to 5.42	SB	135-140	Irrigated conditions	Odisha	Resistant to BPH, tolerant to leaf folder, gundhi bug and WBPH

Note: LB: Long bold, LS: Long slender, SB: Short bold, BPH: Brown plant hopper and WBPH: White backed plant hopper; *Yield as per AICRIP trails.

These stresses, particularly brown plant hopper infestations and associated hopper burn, can result in catastrophic yield losses ranging from 70% to complete crop failure (Min et al., 2014; Jena et al., 2015; Pandi et al., 2018). Integrating such varieties into cultivation systems is essential for ensuring crop stability and reducing dependence on chemical control measures. Table 6 outlines the key traits of the biotic stress tolerant varieties examined.

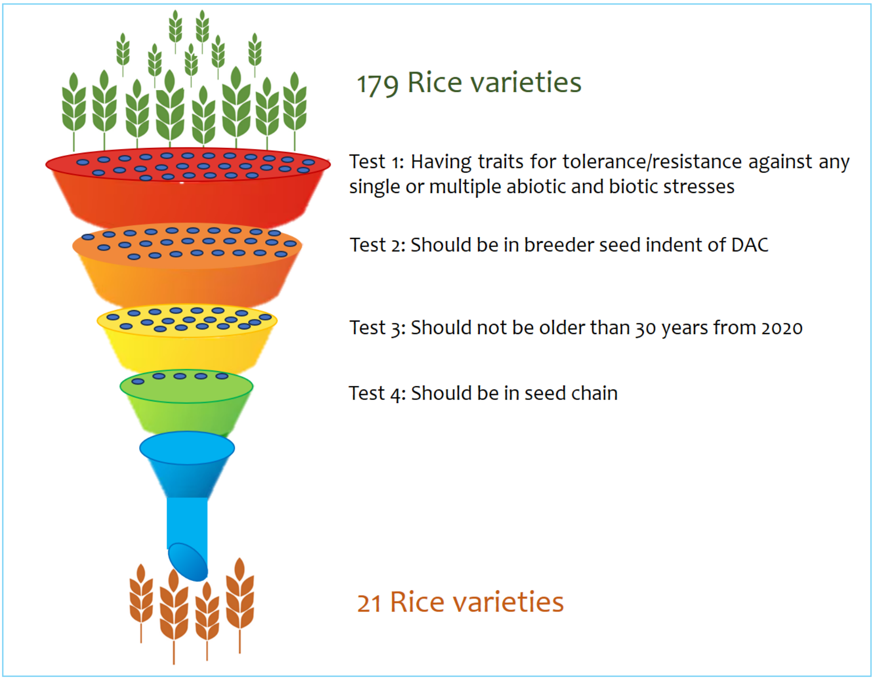
3 Data and Methods

3.1 Technology selection

Data were initially compiled for 179 non-basmati rice varieties developed by ICAR–Central Rice Research Institute. However, many were excluded due to their absence from the formal seed system, which limit the access to their performance and adoption data. A four-stage screening process (Figure 5) was applied to ensure relevance and data availability.

First, varieties with tolerance to one or more abiotic or biotic stresses were shortlisted. Second, those listed in the breeder seed indent of the Department of Agriculture and Cooperation (DAC) were retained. Third, only varieties released within the last 30 years (from 2020) were considered. Finally, inclusion was limited to those currently in the formal seed chain.

Figure 5. Screening criteria for inclusion of rice varieties in the study



Only 21 varieties (Figure 4) met all four criteria and were included in the study.

3.2 Types and levels of impact assessment

An improved crop variety cultivated either in its adoption domain or extend beyond its domain boundary contributes physically through an incremental output, economically by improving income. However, a climate-resilient variety additionally contributes through adding resilience by reducing the downside risk during the stress events. This study assesses the spatial (area coverage), and economic (monetary benefits) impacts of selected climate-resilient rice varieties, at the macro and micro levels.

3.3 Data and variables

Both primary as well as secondary data on different variables were utilized to assess the multifaceted impacts of 21 rice varieties included in the study. Table 7 provides a summary of the variables considered and their respective data sources.

Table 7. Variables used in impact assessment of climate-resilient rice varieties

Variables	Source
Quantity of breeder seed supplied (Q)	ICAR-CRRI, Cuttack
Seed multiplication factor	Seed Net Portal, GoI
Elasticity of supply	Kumar et al., 2010
Elasticity of demand	Kumar et al., 2011
Yield of the variety (t/ha)	ICAR-CRRI, Cuttack
Yield of the competing variety (t/ha)	AICRP reports/FLD reports/ Varietal release proposals
Area (Mha), production (Mt) and yield (t/ha) of the crop in the domain region*	Various issues of agricultural statistics at a glance, GoI
Farm gate price of the crop (Rs. /ton)	Various issues of agricultural prices in India, GoI
Institutional budget (in Rs. crore)	Annual report of past 15 years of ICAR-CRRI, Cuttack
Wholesale price index of paddy	Website of office of the economic advisor

* Estimated from secondary data.

3.4 Analytical procedures

3.4.1 Research cost estimation

Alston et al. (1995), Lenaerts et al. (2019), and White (2023) emphasize the persistent underfunding of cultivar development and the need for strategic resource allocation in agricultural research. A major challenge for breeding programs is the accurate estimation of varietal development costs, for which the economic literature offers limited field-applicable tools.

Almeida and Yokoyama (2000) and Bantilan et al., (2014) systematically added expenditure at each stage of breeding from initial stage to the final release of a crop variety to estimate the research cost. However, Bantilan et al., (2014) reported the challenges in tracing the investments in development of a crop variety as the budget records disaggregated by research program for research conducted at ICRISAT were not available and research investments particularly for a specific crop are difficult to reconstruct in case the institute is working on multiple crops. Subsequently, Wander and da Silva (2022) used an average cost approach, calculating annual expenditures across breeding stages and dividing by the number of varieties released. While suitable for structured, continuous breeding programs, these methods are less applicable in the context where such information is not maintained.

In Indian context, cost estimation is complicated by overlapping projects, shared human resources, difficulty in tracing varietal origins, and lack of standardized cost records. Considering these constraints, this study employed alternative methods better suited to Indian breeding programmes. These are summarized in Figure 6 and discussed in the following section.

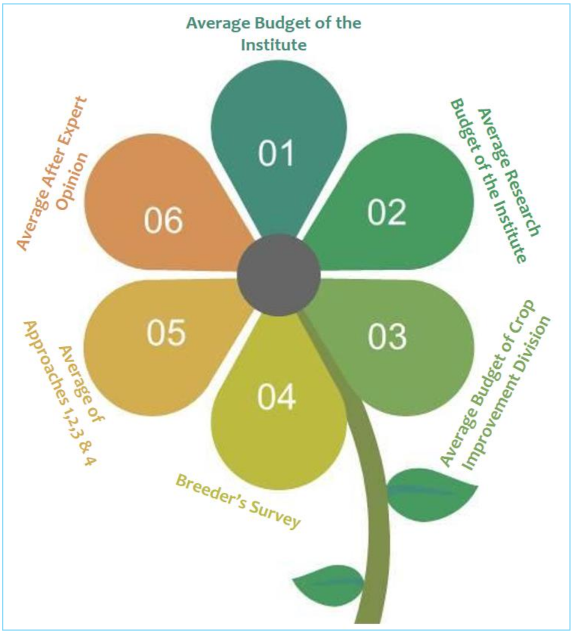
Approach I: Estimation based on average institutional budget

Certain ICAR institutes are crop-specific, with a core mandate to develop improved varieties and associated production technologies. Given the lack of disaggregated cost data for individual variety development, this approach employs the average annual institutional budget per released variety as a proxy for estimating research costs. Since both institutional budgets and varietal release counts vary across years, a 15-year average was used to mitigate year-to-year fluctuations and provide a more stable cost estimate. Formally, the average cost of varietal development per year was estimated as-

$$\text{Research Cost}=\sum_{n=1}^{15}\left(\frac{\text{Cumulative Institute Budget}}{\text{Total Number of Varieties Released}}\right)$$

This method offers an aggregate-level estimate suitable for institutions with long-term breeding mandates but should be interpreted with caution due to its inherent assumptions regarding cost uniformity across varieties.

Figure 6. Methodological approaches for estimating research cost



Approach II: Adjusted estimate based on research allocation

Recognizing that approximately 30% of institutional budgets are allocated to extension and non-research functions, this approach attributes only 70% of the average annual budget per variety (as derived in Approach I) to research activities. Thus, the estimated research cost is:

$$\text{Research Cost}=\left[\sum_{n=1}^{15}\left(\frac{\text{Cumulative Institute Budget}}{\text{Total Number of Varieties Released}}\right)\right]*0.7$$

This adjustment refines the estimate by isolating the portion of the budget attributable to varietal research and development.

Approach III: Division/ Programme level budget attribution

Recognizing that crop-based research institutes undertake a broad spectrum of activities beyond varietal development, this approach isolates the budget of the Crop Improvement Division (or the Genetics and Plant Breeding Division), which is primarily responsible for varietal research. Accordingly, the 15-year average annual budget of the relevant division is used as a proxy for estimating varietal development costs, thereby offering a more targeted and discipline-specific cost approximation.

$$\text{Research Cost}=\sum_{n=1}^{15}\left(\frac{\text{Cumulative Crop Improvement Division Budget}}{\text{Total Number of Varieties Released}}\right)$$

Approach IV: Breeder recall-based cost estimation

Drawing on the methodology of Bantilan et al., (2014) and Wander and da Silva (2022), this approach estimates varietal development costs through breeder-informed recall. An initial exploratory survey was conducted to identify and harmonize the sequential activities involved in the development, evaluation, and release of a new variety. Subsequently, a structured survey was administered wherein breeders were asked to assign cost estimates to each activity based on their memory. The mean cost across all respondents for each activity was then aggregated to derive an overall estimate of varietal development cost. Formally, the total cost was computed as:

$$\text{Research Cost}=\sum_{i=1}^{n}\text{Cost of different activities from initial cross to release of variety}$$

Approach-V (Average of approaches I, II, III and IV): Under this, we took average of research costs obtained from above mentioned approaches to obtained a single value.

$$\text{Research Cost}=\frac{\text{Cumulative cost from Approach I,II, III and IV}}{4}$$

Approach-VI (Average of approaches II, III and IV): Subsequently, we took an expert opinion from senior breeders about the correctness of the value of research costs obtained from each approach and later excluded Approach I due to overestimation in the research cost and took an average of approach II, III and IV to obtain new research cost, which was later triangulated from the breeders for its appropriateness.

$$\text{Research Cost}=\frac{\text{Cumulative cost from Approach II, III and IV}}{3}$$

3.4.2 Estimation of crop varietal area

Farm surveys often yield unreliable varietal adoption data due to the widespread use of local names that may not correspond to officially released varieties (Maredia, 2016; Walker, 2015; Stevenson et al., 2023). In India, Pathak et al. (2018, 2019) proposed indirect methods for estimating varietal area using seed supply data, sample surveys, community assessments, and expert opinion. These methods positioned breeder seed indent as a proxy for varietal adoption, representing the transfer of varietal technology from research to the field.

However, this approach overlook seed system inefficiencies, including supply chain losses and technology transfer through informal seed chain. Moreover, the method does not distinguish between breeder seed demand (indented) and actual supply, which are conceptually distinct. To address these gaps, this study refined the methodology of Pathak et al. (2019) by incorporating a correction factor which accounts for supply chain loss and added an additional component for informal area.

It is assumed that improved varietal technologies exhibit spill over effects, wherein non-adopters acquire seeds from formal adopters after observing performance—reflecting the extension principle of "seeing is believing." Consequently, informal diffusion occurs through farmer-to-farmer exchange of certified or truthfully labelled seeds.

Bisen et al., (2024) incorporated assumptions on varietal discontinuance that are often violated, complicating diffusion estimates. This study refines the model by removing the assumption that second-generation self-retained seed is partially reused or shared, thereby simplifying estimation without significantly affecting gross varietal area.

Accordingly, the revised approach estimates varietal spread as:

$$\text{Area (Ha)} = \frac{(1\text{-SCL})}{\text{SR}} \times \{(\text{BS} \times \text{SMF}) + (\text{Output}_{\text{Gen-I}} \times \text{Output}_{\text{Seed}} \times (1\text{-SRR})\}$$

Where,

BS: Breeder seed supplied by the technology developer (Q)

SMF: Seed multiplication factor of breeder seed

SR: Seed required for planting one hectare of land (Q/ha)

SRR: Seed replacement rate in the domain region (%)

SCL: Supply chain loss

$\text{Output}_{Gen\text{-}I}$: First generation output of technology (tonnes)

Output_{Seed}: Output kept as seed (%)

To estimate seed retention, the per-hectare output was divided by the seed rate required to cultivate that area. This ratio varies by crop, reflecting differences in productivity and seed rate.

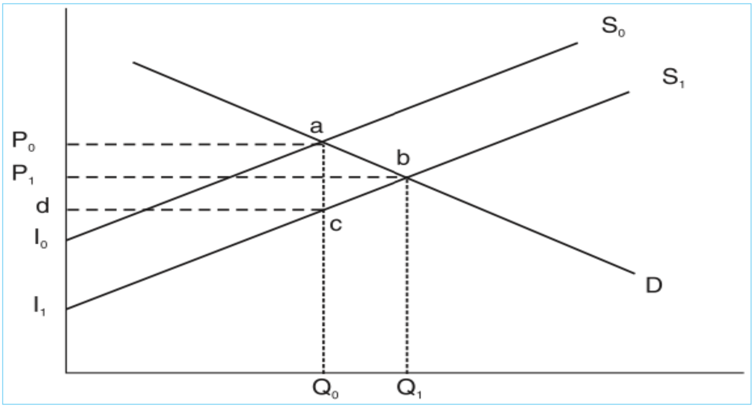
3.4.3 Estimation of economic benefits

To evaluate the aggregate and distributive economic benefits of climate-resilient rice varieties, an economic surplus approach was employed. This method estimates the changes in producer and consumer surplus resulting from shifts in supply and/or demand induced by technological adoption—specifically due to yield improvements and/or input cost reductions.

The model simulates a research-induced supply shift, capturing how technological change affects market equilibrium outcomes. The resulting changes in economic surplus were then discounted at 5% (following Alpuerto et al., 2009; Birthal et al., 2012 and Alston et al., 2020) and aggregated up to 2030 to estimate the total economic gains from the adoption of climate-resilient rice varieties. A closed economy assumption was adopted, considering that the vast majority of rice produced in India is consumed domestically, with minimal influence from international trade. The analytical framework follows the standard economic surplus model proposed by Alston, Norton, and Pardey (1995), as illustrated in Figure 7.

In the figure 7, D represents the market demand curve. The adoption of climate-resilient varieties leads to either yield enhancement or input cost reduction, resulting in a downward shift of the supply curve from S_0 to S_1. The initial market equilibrium was defined by price P_0 and quantity Q_0, while the new equilibrium after technology adoption is P_1 and Q_1. The total annual benefit of the technology-induced supply shift is the area between the two supply curves and under the demand curve, denoted as ΔTS = area I_0abI_1. This total surplus is decomposed into consumer and producer surplus

Figure 7. Economic surplus measurement



as follows:

$$\Delta CS = P_0Q_0Z\ (1 + 0.5Z\eta)$$

$$\Delta PS = P_0\ Q_0\ Z\ (K\text{-}Z)\ (1 + 0.5Z\eta)$$

$$\Delta TS = \Delta CS + \Delta PS = P_0\ Q_0K\ (1 + 0.5Z\eta)$$

Where, ΔCS, change in consumer surplus; ΔPS, change in producer surplus; ΔTS, change in total surplus; P_0, the price before the introduction of climate-resilient rice varieties; Q_0, the pre-research quantity; η, the elasticity of demand.

$$Z = K\varepsilon / (\varepsilon + \eta)$$

$$K = [E(y)/\varepsilon — E\ (c)\ /1 + E(y)]\ pA\ (1 + \partial)$$

Z, reduction in price, relative to its initial value, due to supply shift; η, absolute value of the elasticity of demand; ε, the elasticity of supply; K, proportionate shift down in the supply curve due to the technology; E(y), expected yield change; E(c), expected cost change; p, probability of research success; A, technology adoption rate; ∂, technology depreciation rate.

3.4.4 Estimation of risk-reduction benefits

The Newbery–Stiglitz framework was applied to quantify the economic benefits associated with a reduction in yield variability following the adoption of resilient crop varieties. This model grounded in the theory that risk-averse producers derive utility not only from expected returns but also from reduced uncertainty, with lower yield variance translating into improved income stability (Kostandini et al., 2009).

Let $\overline{Y}_0$ denote the mean yield and σ_{y0} the coefficient of variation for the traditional (non-resilient) variety. Upon adoption of a climate-resilient variety, the mean yield becomes $\overline{Y}_1$ and the coefficient of variation changes to σ_{y1}. The economic value of reduced risk, attributed to the decline in yield variance, is estimated using the following expression:

$$B / \overline{Y}_0 = 0.5\ R\ (\sigma_{y0}^2 - \sigma_{y1}^2)$$

Where,

B is the monetary benefit of reduced yield variability,

R is the coefficient of absolute risk aversion,

σ_{y0} and σ_{y1} are the coefficients of variation for the traditional and resilient varieties, respectively.

The approach underscores the added utility of climate-resilient technologies beyond mean yield improvements by incorporating the value of risk mitigation into the welfare analysis.

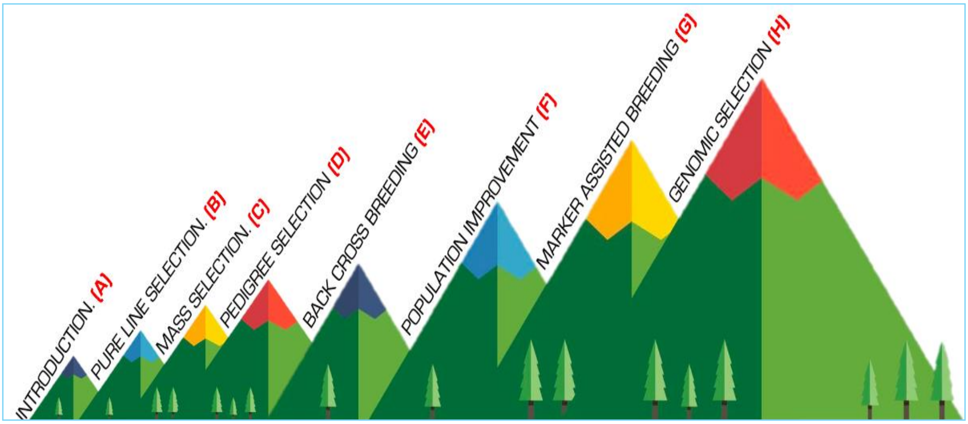
4 Research Cost and Technology Adoption

4.1 Research cost

The research and development (R&D) cost associated with crop varietal development is a function of multiple factors, including the type of inputs utilized, the sequence and intensity of breeding activities, the breeding approach adopted, the geographic location of research operations among others. Traditional breeding approaches such as introduction, pure line selection, mass selection, pedigree-based selection, backcross breeding, and population breeding have historically guided varietal improvement. However, the first three methods—introduction, pure line selection, and mass selection—are now less frequently employed due to the emergence of advanced molecular techniques.

Modern plant breeding increasingly relies on marker-assisted selection (MAS) and genomic selection, especially for self-pollinated crops, due to their ability to accelerate varietal development and enhance precision. While these advanced approaches shorten the breeding cycle, they entail significantly higher financial costs compared to conventional methods. Owing to heterogeneity in breeding programs, it is difficult to disaggregate exact cost structures by breeding approaches. Nonetheless, based on breeders' feedback, a relative cost ordering among different approaches was constructed, as conceptually illustrated in Figure 8.

Figure 8. Conceptual ranking of R&D costs across breeding approaches



Although a general consensus was observed regarding the relative cost hierarchy of breeding methods (ABCDEFGH), some divergence in opinion was also noted. A minority of breeders suggested an alternative sequence (ACBDEFGH), likely attributable to crop-specific contexts, institutional infrastructure, and location-specific cost variations influencing breeding timelines and input intensity.

The empirical estimation of R&D costs for rice varietal development using multiple approaches (as described in the methodology section) is summarized in Figure 9. Among the estimates, Approach I—based on the 15-year average of institute budgets per variety—produced the highest cost estimate at Rs. 9.64 crore. However, this figure is likely overestimated, as it includes non-research expenditures such as infrastructure, administration, and pension liabilities. Conversely, Approach IV, derived from breeder recall surveys, yields the lowest estimate and may underrepresent actual costs.

Figure 9. Estimated research cost (Rs. crore) for varietal development across alternative methodological approaches

Approaches II to IV, which apply more targeted estimations (e.g., budget adjustments for R&D-only functions or division-specific budgets), produced cost estimates ranging between Rs. 2.99 to Rs. 4.65 crore. As part of a refined estimation protocol (Approach VI), we excluded the outlier estimate from

Approach I and computed the average from Approaches II–IV, yielding a more pragmatic R&D cost aligned with expert opinion. When deflated to earlier base years, this estimate is broadly consistent with the rice varietal development costs reported by Shrestha et al. (2012) for Nepal during 2001–2010 at 2000-01 prices.

4.2 Adoption of varietal technologies

The spread of climate-smart rice varieties in the estimation year (2022) indicated a wide disparity across different stress-tolerant categories, reflecting varying degrees of adoption (Figure 10). Drought-tolerant and submergence-tolerant rice varieties demonstrated the highest levels of adoption. Specifically, *Sahabhagi Dhan* and *Swarna Sub 1* dominate with nearly 1.66 million hectares (3.5% of total rice area) each, highlighting their extensive coverage and strong farmer acceptance in drought- and flood-prone ecosystems, respectively. In contrast, other submergence-tolerant varieties like *CR Dhan 505* and *Varsha Dhan* showed more moderate diffusion, with cultivation areas of approximately 73,000 and 62,000 hectares, respectively.

The combined drought- and submergence-tolerant group showed a moderate level of adoption. *CR Dhan 801* leads this segment with about 94,000 hectares, followed by *CR Dhan 802* with around 44,000 hectares, indicating their niche role in areas affected by multiple climatic stresses.

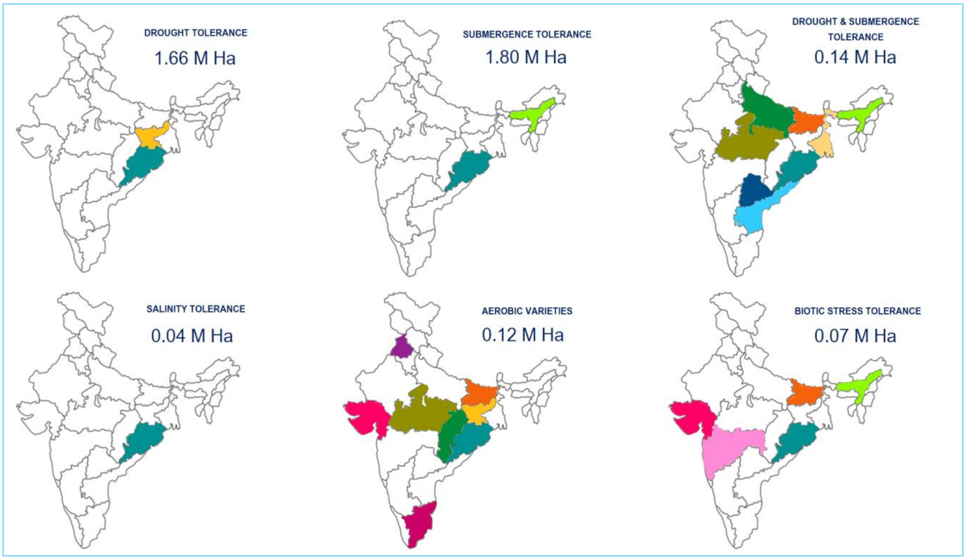
The spread of salinity-tolerant varieties remained limited. *Lunishree, Luna Suvarna*, and *Luna Sampad* collectively account for a relatively small area, ranging between 8,500 and 15,000 hectares each, suggesting more localized or constrained adoption in salinity-prone regions.

Aerobic and upland rice varieties, which are designed for water-saving conditions, showed uneven spread. While *CR Dhan 203* (about 38,000 hectares) and *CR Dhan 210* (19,000 hectares) showed some traction, most others—including *CR Dhan 101, CR Dhan 201*, and *CR Dhan 207*—covered less than 15,000 hectares, pointing to limited reach in upland ecosystems.

Whereas, the biotic stress-tolerant varieties, which aim to reduce losses from pests and diseases, also exhibited modest levels of adoption. Among them, *CR Dhan 311* stood out with approximately 39,000 hectares, whereas *CR Dhan 300* and *CR Dhan 317* both were adopted over 13,000 hectares, respectively.

The observations on the adoption patterns of climate resilient rice varieties seems paradoxical – despite a distinct advantage over their local checks, their adoption was sporadic and limited. And, among the different groups of CRVs, adoption was found biased towards the drought and submergence tolerant varieties. This led to another question why only a few CRVs are preferred over others? In the next section we discussed on the evidences on technology adoption process in agriculture in the context of CRVs included in the study.

Figure 10. Cumulative estimated area under various groups of climate-resilient rice varieties considered in this study within the target region



Source: Authors.

4.3 Drivers and barriers to adoption of climate-resilient rice varieties

The uneven and often limited uptake of climate-resilient rice varieties (CRVs) across domain regions cannot be understood through agronomic performance alone. While earlier sections established that CRVs are stress tolerant, adoption patterns remain patchy across stress types. The reasons lie in the complex interaction of behavioural decision-making, risk perceptions, seed system bottlenecks, institutional incentives, and the invisibility of benefits. These forces collectively explain why drought- and submergence-tolerant varieties were adopted relatively higher than salinity, aerobic, or biotic-stress tolerant lines, and why even within these preferred categories adoption remains far below potential.

4.3.1 Behavioural drivers and the centrality of risk, learning, and observability

Farmers assess new varieties not only on expected yield but on the perceived uncertainty surrounding that yield. The classic insight from Feder et al. (1985)

explained that adoption depends on expected utility under risk—remains highly relevant. Stress-tolerant varieties reduce both downside risk and yield variability, yet these gains are often realized only under stress years and therefore remain partially invisible. Farmers, especially in rainfed ecologies, behave as Bayesian learners; they test new varieties on small plots, wait to observe real-world outcomes, and rely heavily on social learning. This leads to slow, sequential adoption, even when technologies are objectively superior.

The flood-tolerant case illustrates this clearly. Dar et al. (2013) showed that *Swarna-Sub1's* benefits become salient only during flood years. Thus farmers adopt it reactively, as insurance, rather than proactively. Similar patterns hold for drought-tolerant *Sahbhagi Dhan*, whose uptake increased only after farmers personally experienced drought losses. The result is stress-contingent adoption, where demand is triggered by recent shocks rather than long-term risk calculations—leading to sporadic and event-driven diffusion.

However, learning alone does not guarantee scale. Adoption among farmers who merely lived in demonstration villages but never attended field days remained negligible (Emerick & Dar 2021). Only those who engaged directly in demonstrations showed a substantial ($\approx$50%) increase in adoption. This creates a participation bias in extension: the already-informed, better-connected farmers benefit disproportionately, while marginal and socially disadvantaged farmers remain excluded. Evidence consistently shows adoption divides by gender (Mehar et al. 2022), caste (Dar et al. 2013), risk preferences (Ward et al. 2014; 2020), and self-efficacy (Yamano et al. 2015). Social networks reinforce these divides, as information travels unevenly and trust remains confined within homogeneous groups (Yamano et al. 2018; Joshi & Varshney 2022).

4.3.2 Why only a few CRVS are preferred: the visibility problem across stress traits

The dominance of drought- and submergence-tolerant varieties over other CRV groups reflects the visibility and frequency of the stress they address. Droughts and floods are recurrent, severe, and widely experienced in eastern India; their impacts are immediate and memorable. This creates clear demand for insurance-like traits.

By contrast, salinity, aerobic production conditions, and biotic stresses are either chronic but low-visibility (salinity), unfamiliar and management-intensive (aerobic rice), or episodic and unpredictable (biotic stresses). Farmers cannot easily observe the benefits of tolerance traits that matter only under specific or infrequent conditions. This reduces their willingness to replace trusted local varieties.

4.3.3 Supply-side constraints and structural weaknesses in seed systems

Even where farmers exhibit interest, adoption is capped by the weakness of seed delivery systems. Drought-tolerant *Sahbhagi Dhan* was widely praised, yet adoption collapsed in several districts after Cyclone *Titli (October, 2019)* destroyed local seed stocks because formal markets were absent and farmers could not access replacement seed. Similar patterns appear across CRV categories: varietal release does not translate into adoption without sustained seed multiplication, distribution, and branding**.**

Salinity-tolerant varieties illustrate this structural failure most clearly. Despite policy attention, seed availability remains limited, fragmented, and overly dependent on temporary NGO or institutional research projects. In saline pockets of Odisha and the Sundarbans farmers revert to traditional varieties not because improved lines underperform, but because they are not regularly available.

Aerobic rice faces even more entrenched supply-side constraints. Farmers require new machinery, weed management protocols, and herbicides—raising transaction costs far beyond seed access. The technology feels riskier, more complex, and more labour-intensive, nullifying its theoretical benefits.

4.3.4 Institutional incentives and local organisational capacity

Adoption is further shaped by the institutional landscape: proximity to KVKs, ICAR institutes and SAUs, quality of extension, state-level incentives, and strength of FPOs or community seed enterprises. Where institutional capacity is high—as in certain clusters of Odisha (Cuttack, Kendrapada, Jajpur, Badamba, Niali, etc.)—adoption of stress-tolerant varieties accelerates. But in areas with weak local institutions, diffusion stalls even when varieties are agronomically superior.

5 Macro Level Impacts of Climate-Resilient Rice Varieties

Between 1995 to 2020, floods and droughts were India's most frequent climate disasters, affecting 29 and 23 states, respectively (Gupta et al., 2021). Even the current year 2025 witnesses flood in many parts of country affecting rice fields. These events have severely impacted rice production in key states. Future climate projections suggest more extreme weather, increasing yield losses, costs, and livelihood risks (Li et al., 2024; Galle & Katzenberger, 2025). In this context, this chapter provides the macro level evidence for the economic and risk-reduction benefits accrued due to adaptation of climate-resilient rice varieties which are presumed to be a crucial adaptation strategy against the adverse impacts of climate change.

5.1 Parameters used in the estimation of economic surplus & yield stability

The table 8 presents key parameters used to estimate the economic surplus and risk reduction benefits of climate-resilient rice varieties (CRVs), with prices standardized to 2022–23 levels for comparability across release years. The production-weighted farm harvest price **(P_0)** reflects the real economic value per ton of rice at varietal release. The cumulative production at release (Q_0) captures the production scale in the varietal domain, influencing the magnitude of potential surplus.

The yield gain (%) defined as the yield advantage over a popular check variety, is central to estimating producer benefits. High-yielding varieties such as *CR Dhan 207* (42.87%), *Luna Sampad* (32.26%), and *Sahabhagi Dhan* (31.25%) offer significant productivity gains. The current adoption (%) denotes varietal area share as of 2022–23, with *Swarna Sub 1* and *Sahabhagi Dhan* adopted in large area delivering realized benefits. The maximum adoption potential **(A_{max})**, derived from adoption trends, reflects scalability.

Risk reduction is assessed through the coefficient of variation (CV) in farm-level yields. Lower CV_{CRV} relative to CV_{Check} suggests improved yield stability. Varieties such as *Sahabhagi Dhan* (2.34 vs. 20.10) and *Swarna Sub 1* (0.92 vs. 19.20) show substantial risk mitigation, enhancing resilience under climatic stresses like droughts and submergence, respectively. Other varieties like *CR Dhan 210* demonstrate notable CV reduction despite high baseline variability (9.03 vs. 21.63), indicating improved yield stability.

Additionally, the study has taken a few common parameters across all the varietal technologies which are indicated in table 9 given below.

Table 8. Key parameters for estimating economic surplus and risk-reduction benefits of climate-resilient rice varieties

Varietal technologies	P_0 (Rs. / Ton)	Q_0 (000' T)	Yield gain (%)	Current adoption (%)*	A_{max} (%)	CV_{CRV}	$CV_{Non\text{-}CRV}$
Sahabhagi Dhan	17221.27	8455.87	31.25	30.86	33.06	0.02	0.20
Swarna Sub 1	17609.51	6917.47	22.65	42.13	45.14	0.01	0.19
CR Dhan 505	15093.25	13149.10	21.25	1.16	1.93	0.01	0.10
Varsha Dhan	16526.61	6824.70	25.34	1.56	2.16	0.05	0.12
CR Dhan 801	17663.68	60519.20	11.52	0.40	1.50	0.01	0.12
CR Dhan 802	9904.73	16060.70	5.61	0.82	3.06	0.01	0.17
Lunishree	13344.07	5387.70	19.05	0.38	0.56	0.06	0.22
Luna Suvarna	17311.33	6827.72	28.57	0.22	0.25	0.09	0.18
Luna Sampad	17311.33	6827.72	32.26	0.38	0.43	0.06	0.18
CR Dhan 101	16283.02	8286.10	10.34	0.33	0.55	0.02	0.16
CR Dhan 201	15171.73	12398.40	11.95	0.22	0.37	0.05	0.18
CR Dhan 202	16241.07	11605.80	28.09	0.21	0.36	0.12	0.20
CR Dhan 203	16283.02	8286.10	13.44	0.97	1.62	0.02	0.14
CR Dhan 204	16835.75	9158.70	21.54	0.52	0.87	0.03	0.13
CR Dhan 205	18040.61	30494.40	9.71	0.19	0.32	0.01	0.15
CR Dhan 206	16283.02	8286.10	21.87	0.19	0.32	0.01	0.15
CR Dhan 207	16945.65	7733.70	42.87	0.23	0.68	0.07	0.21
CR Dhan 210	16070.02	8765.30	30.64	0.48	2.41	0.09	0.22
CR Dhan 311	19814.15	12540.51	20.48	0.14	0.51	0.06	0.17
CR Dhan 300	13625.92	19539.10	12.85	0.62	0.93	0.02	0.17
CR Dhan 317	16994.55	9290.76	13.63	0.32	2.43	0.01	0.14

*Current Adoption (in %) corresponds to 2022-23.

5.2 Economic surplus due to different climate-resilient rice varieties

The economic surplus estimates derived for different groups of climate-resilient rice varieties (CRVs) provide critical insights into their macroeconomic relevance within the broader climate adaptation framework for Indian agriculture. The analysis is rooted in the economic surplus methodology, which captures welfare changes resulting from technological innovation by estimating gains to both producers and consumers under partial equilibrium framework between the technology inception year and 2030. The distribution of surplus across these two stakeholder groups is notably balanced across all varietal categories, reflecting the relatively inelastic and symmetric nature of rice demand and supply in India—a staple crop with limited substitutes and constrained responsiveness to price fluctuations in both production and consumption.

Table 9. Common parameters used for all varietal technologies

Parameters	Value	Source
Elasticity of supply (ε_s)	0.236	Kumar et al., 2010
Elasticity of demand (ε_d)	0.247	Kumar et al., 2011
Probability of research success	1.00	-
Depreciation rate in initial 15 years after the release of technologies	0.00	Expert opinion
Discount rate (%)	5.00	Brennan and Malabayabas, 2011; Rejesus et al., 2014; Raitzer et al., 2015 and Alston et al., 2020
Seed multiplication ratio	80.00	www.seednet.gov.in
% Reduction in cost due to new variety	5.00	Expert opinion and FGD
Relative risk aversion coefficient	3.10	Fafchamps and Pender (1997)

The results showed that drought-tolerant varieties, particularly those adopted in Jharkhand and Odisha, has highest potential aggregate surplus—Rs. 1,08,388.76 crore which is equivalent to Rs. 5161 crore of annual value (≈34% of annual value of output in the domain region)—indicating the high marginal value of technological intervention in water-scarce ecosystems. With producer and consumer surplus at Rs. 55,463.07 and Rs. 52,925.69 crore, respectively (Table 10), the variety highlights its ability to simultaneously enhances resilience and contributes to supply-side stability, thus dampening upward price pressures. This is especially important in semi-arid and rainfed areas where production volatility translates directly into food insecurity and rural income instability.

Table 10. Economic benefits due to climate-resilient rice varieties (Rs. crore)

Trait specific varietal groups	Consumer surplus	Producer surplus	Economic surplus
Drought tolerant	52925.69	55463.07	108388.76
Submergence tolerant	38983.90	40852.87	79836.77
Drought & submergence tolerant	3033.97	3179.43	6213.40
Salinity tolerant	1486.06	1557.31	3043.37
Aerobic varieties	5186.85	5435.52	10622.37
Biotic stress tolerant	1430.37	1498.95	2929.32
Total	**103046.84**	**107987.14**	**211033.98**

Similarly, submergence-tolerant varieties adopted in flood-prone regions such as Assam and Odisha displayed the potential economic surplus of Rs. 79836.77 crore which is equivalent to Rs. 3842 crore of annual value (≈19% of annual value of output in the domain region). By enabling the crop to tolerate 14 days of submergence and survive thereafter, these varieties mitigate yield losses from recurrent flash floods which have become increasingly frequent due to changing monsoon patterns.

In regions subject to compound climate risks—including states such as Andhra Pradesh, West Bengal, Bihar, and Madhya Pradesh—the adoption of varieties tolerant to both drought and submergence has displayed a modest but economically meaningful potential economic surplus of Rs. 6213.40 crore (≈0.5% of annual value of output in the domain region when converted to annual value). These varieties, though less widely adopted, offer critical adaptive value in regions where the convergence of multiple stressors intensify production uncertainty.

The economic surplus from salinity-tolerant varieties (Rs. 3043.74 crore; ≈1% of annual value of output in the domain region when converted to annual value), though smaller in magnitude, is significant in coastal agro-ecologies like Odisha, where rising sea levels and salt water intrusion threaten land productivity. Similarly, aerobic rice varieties, developed for low-input and water-limited environments, yield an estimated economic surplus of Rs. 10,622.37 crore (≈0.9% of annual value of output in the domain region when converted to annual value) across the domain region. These varieties are increasingly gaining importance as groundwater depletion and climate-induced water stresses are escalating in traditionally irrigated areas. Their adoption supports input-use efficiency and risk mitigation without compromising yield.

Biotic stress-tolerant varieties, with a surplus of Rs. 2929.32 crore (≈0.6% of annual value of output in the domain region when converted to annual value), reflect the moderate economic potential due to relative younger age of the varietal technology, but promises income stability under growing challenge of pest and disease pressure under climate change. As temperature and humidity regimes shift, the incidence and intensity of biotic stresses are likely to rise, making these varieties a key pillar of anticipatory adaptation strategies.

5.3 Risk-reduction benefits due to climate-resilient rice varieties

The estimation of risk-reduction benefits from climate-resilient rice varieties (CRVs) draws on the Newbery–Stiglitz expected utility framework, which remains one of the few formal approaches capable of capturing farmer risk preferences under uncertainty. By adopting a coefficient of relative risk aversion of 3.10, consistent with Fafchamps and Pender (1997) for smallholder farmers in India, the analysis reflects the increased vulnerability of households operating without effective insurance or credit market. This behavioural parameter is critical as the welfare value of CRVs is disproportionately tied to variance-reducing traits, yet these traits are often undervalued in conventional breeding pipelines and policy evaluation metrics that continue to augment mean yield gains. Estimating risk-reduction benefits from the technology's inception year through 2030 therefore provides not only a forward-looking measure of resilience but also a corrective to existing evaluation frameworks that inadequately account for climate-induced volatility.

The results reveal stark spatial contrasts that mirror India's uneven climate exposure. Drought-tolerant varieties in Jharkhand and Odisha deliver an estimated Rs. 4912.59 crore (Table 11) in risk-reduction underscoring the chronic neglect of rainfed regions in India's irrigation-centric policy architecture.

Table 11. Macroeconomic risk benefits (Rs. crore) due to climate-resilient rice varieties

Trait specific varietal groups	Risk-reduction benefits		Share (%) in value of Output of Paddy* in	
	Cumulative	Annual	Domain	India
Drought tolerant varieties	4912.59	234	1.54	0.106
Submergence tolerant varieties	4474.22	214	1.03	0.097
Drought & submergence tolerant varieties	474.59	43	0.03	0.020
Salinity tolerant varieties	104.99	4	0.03	0.002
Aerobic varieties	547.11	41	0.04	0.019
Biotic stress tolerant varieties	158.79	14	0.03	0.007
Total	**10672.29**	**550**	-	**0.025**

*Share corresponds to the year 2022-23.

Similarly, yield stabilization benefits due to submergence-tolerant varieties in Assam and Odisha was Rs. 4474.22 crore, demonstrating that yield-stabilizing technologies can substantially offset losses in ecosystems repeatedly exposed to flooding. However, despite these large welfare gains, adoption in flood-prone regions remains below potential, pointing to systemic failures in varietal replacement mechanisms, seed supply chains, and last-mile delivery.

In multi-hazard ecologies spread across Andhra Pradesh, Telangana, Bihar, West Bengal, Uttar Pradesh, Madhya Pradesh, and Odisha, dual-stress tolerant varieties yield Rs. 474.59 crore in risk-reduction benefits. Although modest relative to single-stress varieties, their value is strategically significant, these ecologies face compound and sequential shocks, yet climate-smart varietal portfolios remain thin, and breeding pipelines for multi-trait cultivars receive comparatively little institutional prioritization. This mismatch between emerging risk profiles and varietal offerings highlights a structural lag in India's adaptation system.

The Rs. 104.99 crore in yield stabilization benefits from salinity-tolerant varieties, concentrated in coastal Odisha, often compensates for slow-onset hazards such as sea-level rise and saline intrusion. The benefits from salinity-tolerant varieties, though geographically constrained, point to an urgent need to integrate varietal deployment with broader coastal adaptation strategies, including embankment strengthening, controlled drainage, and soil reclamation.

The effectiveness of aerobic rice varieties, with Rs. 547.11 crore in risk-reduction value across Bihar, Chhattisgarh, Gujarat, Jharkhand, and Tamil Nadu, should also be viewed critically. These varieties offer resilience under declining groundwater and erratic monsoons, yet the shift to direct-seeded, non-puddled systems has been slow due to labour constraints, weed pressures, and limited extension support. Without complementary investments—particularly in mechanization and water-saving agronomy—the full resilience potential of aerobic systems will remain unrealized.

Finally, biotic stress-tolerant varieties generated Rs. 158.79 crore in yield stabilization benefits across Assam, Bihar, Maharashtra, and Odisha. Their comparatively smaller magnitude reflects both the early stage of these breeding efforts and the policy blind spot around climate-sensitive pest and disease pressures—an area where surveillance, forecasting, and rapid-response systems lag significantly behind emerging risks.

5.4 Net present benefits due to adoption of climate-resilient rice varieties

The net present value (NPV) estimates of yield and risk benefits from the adoption of CRVs, discounted at 5%, offer compelling economic justification for mainstreaming these varieties within India's climate adaptation strategy. However, a more critical reading of these results reveals that the economic viability of CRVs is neither automatic nor uniform; it is contingent on varietal performance parameters and the enabling institutional environment. The quantified benefits arise from two channels: (i) yield gains, reflecting the performance advantage of CRVs over their respective check varieties, and (ii) risk-reduction benefits, which capture their capacity to reduce yield variability under climatic stress. Both are highly sensitive to two underlying factors—the magnitude of yield advantage and the degree of yield variability reduction—each shaped by field-level agro-ecological realities, management practices, and the effectiveness of seed dissemination pathways.

To strengthen technical credibility, the analysis employs variety-wise yield data from multi-location varietal trials, enabling a more rigorous comparison between CRVs and their check varieties. This evidence base avoids the common pitfall of relying on limited on-station data and instead captures yield differentials and variability across heterogeneous environmental conditions. Consequently, the estimates of yield surplus and stability benefits are grounded in a dataset that reflects real-world stress heterogeneity. Percentage yield gains thus reflect observed performance across diverse agro-ecologies, while the risk-reduction estimates rely on differences in the coefficient of variation between CRVs and checks under stress-prone environments.

Yet, despite the methodological robustness, the results highlight structural asymmetries in the distribution of benefits. Drought-tolerant varieties report the highest total NPV at Rs. 49,844.77 crore, driven overwhelmingly by yield advantages (Rs. 47,614.29 crore) and supported by Rs. 2,230.48 crore in stability benefits (Table 12). This concentration of value suggests both the severity of drought risks in India's rainfed systems and the longstanding policy neglect of these regions—gaps that CRVs are currently compensating for, rather than structural solutions being put in place. Submergence-tolerant varieties, with a total NPV of Rs. 12,501.16 crore and Rs. 657.48 crore in risk-related benefits, illustrate a similar pattern: varietal innovations are delivering resilience in ecologies where flood-preparedness, drainage infrastructure, and early-warning systems remain inadequate.

Varieties tolerant to both drought and submergence show a higher sensitivity to risk benefits, with 6.93% of their Rs. 2,096.89 crore total NPV attributable to yield stabilization. This disproportionate contribution underscores the emerging relevance of multi-stress breeding in a context where compound climate risks are becoming the norm. However, the relatively moderate aggregate NPV points toward slow adoption, insufficient seed multiplication, and the absence of targeted stress-zone varietal replacement programs.

Patterns observed for aerobic and biotic-stress tolerant varieties, where risk-related benefits constitute 4–5% of total value, highlight another systemic limitation: while these varieties respond to increasingly prevalent biophysical risks—groundwater scarcity and climate-sensitive pest outbreaks—the supporting agronomic and surveillance systems remain underdeveloped. Without investments in water-saving agronomy, pest forecasting, and integrated seed systems, the full resilience value of these technologies will remain unrealized.

Table 12. Cumulative discounted benefits (Rs. crore) from the adoption of climate-resilient rice varieties

Trait specific varietal groups	Yield benefits	Risk benefits	Total benefits
Drought tolerant varieties	47614.29	2230.48	49844.77
Submergence tolerant varieties	11843.67	657.48	12501.16
Drought & submergence tolerant varieties	1951.66	145.23	2096.89
Salinity tolerant varieties	456.27	15.83	472.10
Aerobic varieties	694.51	31.83	726.34
Biotic stress tolerant varieties	858.47	43.08	901.55
Total	**63418.87**	**3123.94**	**66542.81**

The salinity-tolerant varieties, offering the lowest relative risk share at 3.35%, point to a deeper structural issue: slow-onset climate hazards such as salinity intrusion remain peripheral in India's adaptation planning, resulting in limited breeding investment, slow varietal replacement, and poor integration with coastal protection measures.

6 Farm-Level Impacts of Climate-Resilient Rice Varieties

This chapter presents the farm level implications of adopting climate-smart rice varieties. The findings have important implications for technology targeting and extension strategies to introduce and scale up resilience in farming against climate change.

6.1 Expected benefits from cultivation of climate-resilient rice varieties

The farm-level economic assessment of climate-resilient rice varieties demonstrated that the adoption of trait-specific cultivars can generate substantial annual benefits for farmers, although the magnitude and structure of these benefits vary across stress environments. Across all varietal groups, the benefits were driven by yield gains—ranging from Rs. 16,460.78/ha for drought–submergence tolerant cultivars to Rs. 45,035.30/ha for drought-tolerant varieties—while yield stability contributed a smaller yet meaningful supplementary gain (between Rs. 1,079.62/ha and Rs. 2,125.21/ha) (Table 13). This clear dominance of yield-enhancing effects indicates that climate-resilient varieties function not only as adaptive tools against climatic shocks but also as productivity-enhancing technologies capable of improving baseline incomes for rice farmers.

Table 13. Expected benefit (Rs./ha) from adoption of climate-resilient rice varieties

Trait specific varietal groups	Expected benefits due to -		Total benefits
	Yield gain	Yield stability	
Drought tolerant varieties	45035.30	2125.21	47160.51
Submergence tolerant varieties	30804.32	1723.64	32527.97
Drought & submergence tolerant varieties	16460.78	1079.62	17540.40
Salinity tolerant varieties	35479.84	1628.34	37108.19
Aerobic varieties	37689.13	1909.17	39598.30
Biotic stress tolerant varieties	25398.82	1463.69	26862.51

Among the varietal groups assessed, drought-tolerant and aerobic rice varieties provide the highest economic returns, with total benefits of Rs. 47,160.51/ha and Rs. 39,598.30/ha respectively. These varieties generate large yield gains (Rs. 45,035.30/ha for drought-tolerant and Rs. 37,689.13/ha for aerobic) complemented by notable stability advantages. Their high per-hectare returns underscore the critical role of stress-tolerant breeding in India's drought-prone agroecologies, particularly where rainfall variability, groundwater depletion, and prolonged dry spells have become increasingly common. For farmers in these regions—often smallholders with limited risk-bearing capacity—these varieties offer a pathway to enhance yield reliability, reduce crop failure risk, and stabilise annual farm incomes without requiring additional water, input use, or major shifts in cultivation practices.

Salinity-tolerant rice varieties also provide strong economic gains, delivering total benefits of Rs. 37,108.19/ha, with yield gains contributing Rs. 35,479.84/ha. This high benefit profile is notable for coastal and inland saline tracts, where sea-level rise, cyclone-driven seawater inundation, and rising soil salinity threaten the viability of traditional rice varieties. For farmers in these locations—many of whom face chronic yield losses—salinity-tolerant varieties represent a low-cost, high-return adaptation option that directly mitigates soil and water constraints.

Biotic stress-tolerant varieties yield moderate but relevant benefits of Rs. 26,862.51/ha, largely through yield gains of Rs. 25,398.82/ha. Although their economic advantage is lower compared to abiotic stress-tolerant cultivars, they carry additional indirect benefits for farmers, including reduced pesticide expenditure, lower exposure to chemical hazards, and diminished vulnerability to pest outbreaks that are expected to intensify under climate change. Their adoption therefore supports both economic and health-related welfare outcomes, especially in regions with high pest incidence.

In contrast, the combined drought and submergence tolerant varieties exhibit the lowest benefit estimate at Rs. 17,540.40/ha. Their relatively modest yield gain (Rs. 16,460.78/ha) and stability effect (Rs. 1,079.62/ha) may reflect either biological trade-offs in stacking multiple stress-tolerance traits or the less frequent occurrence of dual stresses in many rice-growing regions. While these varieties remain important for specific ecologies, the results suggest a need for more targeted investment in improving multi-stress tolerance and ensuring that such varieties meet both productivity and resilience expectations at the farm level.

7 Conclusion and Way Forward

Climate change has emerged as one of the most formidable threats to India's rice economy, imposing recurring shocks that disproportionately burden small and marginal farmers who lack the buffers needed to withstand climatic uncertainty. The evidence presented in this assessment demonstrates unequivocally that climate-resilient rice varieties (CRVs) offer a cost-effective and scalable adaptation pathway, with the potential to enhance productivity, reduce production volatility, stabilise rural incomes, and generate significant welfare gains at both micro and macro levels. The study monetizes these benefits by quantifying two distinct but interrelated effects—yield enhancement and risk reduction—and shows that CRVs deliver not only higher mean yields but also substantial reductions in downside losses during stress years. Together, these findings underscore the fundamental role of resilient varietal technologies as a farmer-centric and system-level adaptation strategy for India's increasingly unpredictable climate.

At the macro level, the cumulative economic surplus generated by CRVs is projected at Rs. 2,11,033.98 crore by 2030, with drought-tolerant varieties alone contributing more than Rs. 1,08,388 crore and submergence-tolerant varieties adding Rs. 79,836 crore to national welfare. These gains reflect the scale of climate-induced yield penalties avoided by shifting to stress-tolerant varieties. When disaggregated, both producers and consumers benefit almost equally, revealing that CRVs enhance not only farm incomes but also broader market stability—particularly by moderating price spikes during stress-induced supply contractions.

Complementing these production gains, the estimated risk-reduction benefits amount to Rs. 10,672 crore, a figure that captures the stabilizing impact of reduced yield variability. For millions of farmers operating in rainfed, flood-prone, coastal saline, or pest-affected areas, this risk mitigation is economically transformative. The ability to reduce the probability of crop failure—often the difference between meeting annual consumption needs and falling into debt—illustrates the crucial insurance-like value that conventional productivity-focused metrics overlook. Drought-tolerant varieties alone account for Rs. 4,912.59 crore of these risk benefits, followed by submergence-tolerant varieties with Rs. 4,474.22 crore, reflecting the severe and recurring nature of these stresses across eastern and central India.

The farm-level assessment further reinforces these insights by quantifying per-hectare benefits accruing directly to farmers. Aerobic and drought-tolerant varieties provide the highest total farm-level gains—Rs. 39,598/ha and Rs. 47,160/ha, respectively—while salinity-tolerant and submergence-tolerant varieties offer sizeable benefits of Rs. 37,108/ha and Rs. 32,528/ha. Importantly, these gains are not restricted to yield alone: yield stability contributes an additional Rs. 1,000–Rs. 2,100/ha across varietal groups, cushioning farmers against severe losses during climatic extremes. These results decisively demonstrate that non-adoption of CRVs implies a sizeable opportunity cost for farmers, particularly in ecologies where climate stresses are recurrent.

Yet, despite these documented agronomic and economic advantages, the adoption of CRVs remains heterogeneous and often far below potential. Drought-tolerant Sahbhagi Dhan and submergence-tolerant Swarna-Sub1 dominate adoption, jointly accounting for more than 3.3 million hectares, while salinity-tolerant, aerobic, dual-tolerant, and biotic stress-tolerant varieties remain restricted to relatively small pockets. The study identifies several drivers behind this uneven uptake: limited visibility of benefits in non-stress years, risk-averse behaviour among smallholders, quality and availability constraints in the seed supply chain, and inadequate extension support—particularly in regions lacking institutional density. These barriers reflect structural weaknesses in India's technology dissemination ecosystem rather than shortcomings in varietal performance.

The evidence suggests that climate-resilient varietal technologies represent a high-return adaptation investment with strong equity implications, and that accelerating their adoption can significantly enhance the resilience of India's rice production system. A strategic policy framework, therefore, must aim to strengthen varietal delivery systems, integrate CRVs into climate planning, and support farmers in managing risk more effectively.

Way forward

Building on the evidence generated in this study, a coherent and actionable policy pathway is necessary to unlock the full potential of climate-resilient rice varieties (CRVs) in strengthening India's food system and safeguarding farmer livelihoods under accelerating climate risks.

The first priority should be to institutionalise resilience-focused crop improvement by embedding stress-tolerance traits—such as drought, submergence, salinity, heat, and major biotic resistances—as core requirements in all future rice breeding programmes across ICAR and State Agricultural Universities. This calls for a coordinated national breeding framework that leverages molecular tools, multi-stress screening platforms, and long-term dedicated funding within existing crop improvement missions.

A second imperative should be on establishing a robust, region-specific seed delivery architecture that ensures reliable and timely access to CRV seed in climate-vulnerable districts. Strengthening breeder and foundation seed production, developing decentralised seed hubs through State Seed Corporations, FPOs, and women-led seed enterprises, and integrating CRVs into national and state seed indents, minikits, and RKVY–NFSM seed distribution schemes can significantly reduce the current supply bottlenecks.

The third policy action should be on systematic integration of CRVs into climate adaptation and disaster-risk management frameworks. Embedding stress-specific varietal advisories in District Agricultural Contingency Plans, pre-positioning CRV seed stocks at local levels for rapid post-disaster deployment, linking adoption with incentives under the Pradhan Mantri Fasal Bima Yojana, and aligning varietal choice with PMKSY's water-saving initiatives will transform CRVs into frontline tools for risk mitigation.

Fourth, a farmer-centred extension strategy is essential to overcome behavioural barriers that slow adoption. Multi-year field demonstrations in high-risk clusters, locally relevant advisories through KVKs, digital and mobile-based decision-support services, and the involvement of community champions—including women and tribal farmers—can make resilience benefits more visible and build trust in new varieties before climatic shocks occur.

Finally, public investment should be strategically targeted toward high-vulnerability geographies and underserved farmer groups, where both the need and potential impact of CRVs are greatest. This involves prioritising districts consistently affected by drought, floods, and salinity using NICRA vulnerability assessments, and offering localised incentives—such as seed subsidies, procurement preference, and logistical support—to promote CRVs in these regions. Integrating CRV dissemination with rural livelihood missions and tribal development programmes will ensure equitable access for the most climate-exposed communities.

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Appendix

Appendix-I

Adoption and spread of climate-resilient rice varieties

Attributes	Varieties	Release year	Estimated varietal area (Mha)	Estimated adoption# (%)
Drought tolerant	*Sahabhagi Dhan*	2009	1.664	30.86
Submergence tolerant	*Swarna Sub 1*	2009	1.663	42.13
	CR Dhan 505	2014	0.073	1.16
	Varsha Dhan	2006	0.062	1.56
Drought & submergence tolerant	*CR Dhan 801*	2019	0.094	0.40
	CR Dhan 802 (2025)	2019	0.044	0.82
Salinity tolerant	*Lunishree*	1992	0.015	0.38
	Luna Suvarna	2010	0.009	0.22
	Luna Sampad	2010	0.015	0.38
Aerobic/Upland rice	*CR Dhan 101 (2025)*	2014	0.013	0.33
	CR Dhan 201	2014	0.002	0.22
	CR Dhan 202 (2025)	2014	0.004	0.21
	CR Dhan 203	2014	0.038	0.97
	CR Dhan 204	2014	0.019	0.52
	CR Dhan 205	2014	0.012	0.19
	CR Dhan 206	2014	0.008	0.19
	CR Dhan 207 (2023)	2018	0.001	0.23
	CR Dhan 210 (2025)	2020	0.019	0.48
Biotic stress tolerant	*CR Dhan 300 (2024)*	2019	0.013	0.14
	CR Dhan 311 (2025)	2013	0.039	0.62
	CR Dhan 317 (2025)	2021	0.013	0.32

#Estimated adoption is for the domain region. Estimates for CR Dhan 101, 202, 210, 311, 317 and 802 are for 2025; For CR Dhan 207 and CR Dhan 300 it is for the year 2023 and 2024. For the remaining varieties, estimates correspond to 2022.

Multi-location yield and coefficient of variation in yield of climate-resilient and traditional rice varieties

Varietal tech	Yields of CRV (t/ha)			CV in yield	Yields of non-CRV (t/ha)			CV in yield	Yield advantage (%)
	L1	L2	L3		L1	L2	L3		
Sahabhagi Dhan	3.73	3.85	3.95	0.02	3.29	2.83	1.98	0.20	31.25
Swarna Sub 1	5.42	5.37	5.30	0.01	4.77	3.65	3.00	0.19	22.65
CR Dhan 505	4.85	4.72	4.69	0.01	4.00	3.32	3.19	0.10	21.25
Varsha Dhan	3.69	3.87	4.20	0.05	4.39	3.87	3.28	0.12	25.34
CR Dhan 801	4.30	4.30	4.25	0.01	3.90	2.95	3.20	0.12	11.52
CR Dhan 802	4.25	4.30	4.15	0.01	3.20	4.80	4.56	0.17	5.61
Lunishree	4.50	4.36	3.91	0.06	2.01	3.50	2.81	0.22	19.05
Luna Suvarna	4.70	4.15	3.73	0.09	2.80	2.20	1.80	0.18	28.57
Luna Sampad	4.50	4.10	3.90	0.06	2.10	3.30	2.68	0.18	32.26
CR Dhan 101	3.90	4.00	3.83	0.02	2.95	2.00	2.48	0.16	10.34
CR Dhan 201	4.31	3.80	4.00	0.05	3.55	2.28	3.30	0.18	11.95
CR Dhan 202	3.18	4.00	3.09	0.12	2.20	3.19	2.07	0.20	28.09
CR Dhan 203	4.11	4.25	4.30	0.02	3.90	2.76	3.60	0.14	13.44
CR Dhan 204	4.88	5.20	4.90	0.03	3.95	3.85	2.92	0.13	21.54
CR Dhan 205	4.27	4.23	4.20	0.01	2.60	3.78	3.20	0.15	9.71
CR Dhan 206	5.03	5.00	4.90	0.01	4.00	2.74	3.55	0.15	21.87
CR Dhan 207	4.54	4.47	3.85	0.07	2.41	3.33	2.06	0.21	42.87
CR Dhan 210	3.81	3.05	3.51	0.09	4.14	2.71	2.66	0.22	30.64
CR Dhan 311	5.90	5.10	5.68	0.06	3.92	3.85	2.62	0.17	20.48
CR Dhan 300	5.25	5.20	5.00	0.02	2.64	3.98	3.75	0.17	12.85
CR Dhan 317	6.02	6.11	6.04	0.01	5.51	3.89	4.78	0.14	13.63

L1, L2 and L3 indicates yield of crop at three distinct locations.

Change in economic surplus (in Rs. crore) due to adoption of climate-resilient rice varieties

Attributes	Varieties	Consumer surplus	Producer surplus	Economic surplus
Drought tolerant	*Sahabhagi Dhan*	52925.69	55463.07	108388.76
Submergence tolerant	*Swarna Sub 1*	34861.24	36532.57	71393.81
	CR Dhan 505	2126.28	2228.22	4354.50
	Varsha Dhan	1996.37	2092.08	4088.46
Drought & Submergence tolerant	*CR Dhan 801*	2587.18	2711.22	5298.40
	CR Dhan 802	446.79	468.21	915.00
Salinity tolerant	*Lunishree*	391.89	410.68	802.58
	Luna Suvarna	381.69	399.99	781.68
	Luna Sampad	712.48	746.63	1459.11
Aerobic/Upland rice	*CR Dhan 101*	217.64	228.08	445.72
	CR Dhan 201	217.48	227.91	445.39
	CR Dhan 202	569.26	596.55	1165.82
	CR Dhan 203	823.16	862.63	1685.79
	CR Dhan 204	557.40	584.13	1141.53
	CR Dhan 205	378.39	396.53	774.91
	CR Dhan 206	278.28	291.62	569.90
	CR Dhan 207	519.61	544.52	1064.14
	CR Dhan 210	1625.62	1703.55	3329.17
Biotic stress tolerant	*CR Dhan 300*	108.64	113.85	222.49
	CR Dhan 311	557.98	584.73	1142.72
	CR Dhan 317	763.75	800.37	1564.12

Appendix-IV

Risk benefits (in Rs. crore) due to climate-resilient rice varieties over the study period

Attributes	Varieties	Risk-benefits
Drought tolerant	*Sahabhagi Dhan*	4912.59
Submergence tolerant	*Swarna Sub 1*	4328.48
	CR Dhan 505	78.71
	Varsha Dhan	67.03
Drought & submergence tolerant	*CR Dhan 801*	265.79
	CR Dhan 802	208.79
Salinity tolerant	*Lunishree*	42.01
	Luna Suvarna	20.12
	Luna Sampad	42.87
Aerobic/Upland rice	*CR Dhan 101*	42.52
	CR Dhan 201	44.61
	CR Dhan 202	41.32
	CR Dhan 203	96.91
	CR Dhan 204	32.37
	CR Dhan 205	74.76
	CR Dhan 206	22.75
	CR Dhan 207	34.76
	CR Dhan 210	157.11
Biotic stress tolerant	*CR Dhan 300*	14.23
	CR Dhan 311	55.71
	CR Dhan 317	88.86

Appendix-V

Per hectare per annum yield and risk benefits (in Rs./ha) due to adoption of climate-resilient rice varieties

Attributes	Varieties	Yield benefits	Risk-benefits	Total-benefits
Drought tolerant	*Sahabhagi Dhan*	45035.30	2125.21	47160.51
Submergence tolerant	*Swarna Sub 1*	27189.71	1660.77	28850.48
	CR Dhan 505	2115.98	38.28	2154.25
	Varsha Dhan	1498.64	24.59	1523.23
Drought & submergence tolerant	*CR Dhan 801*	15035.26	754.30	15789.57
	CR Dhan 802	1425.52	325.31	1750.83
Salinity tolerant	*Lunishree*	7763.74	702.00	8465.75
	Luna Suvarna	9346.46	295.06	9641.52
	Luna Sampad	18369.64	631.28	19000.92
Aerobic/Upland rice	*CR Dhan 101*	1235.27	117.85	1353.12
	CR Dhan 201	2166.52	217.00	2383.52
	CR Dhan 202	3361.58	119.15	3480.73
	CR Dhan 203	4699.69	270.25	4969.94
	CR Dhan 204	3938.35	111.70	4050.05
	CR Dhan 205	2120.80	204.61	2325.41
	CR Dhan 206	1583.41	63.20	1646.61
	CR Dhan 207	4998.99	163.36	5162.35
	CR Dhan 210	13584.53	642.04	14226.57
Biotic stress tolerant	*CR Dhan 300*	3713.40	322.46	4035.86
	CR Dhan 311	11261.31	548.96	11810.27
	CR Dhan 317	10424.10	592.27	11016.38

Note: Estimates indicates the adoption weighted benefits.

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