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Traditional Rice as a Source of Gene Pool for Stress Resilience and Development of Climate-Smart Genotypes for Future Food Security

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ABSTRACT

Rice (*Oryza sativ*a L.) is a major staple crop supporting global food security, particularly in Asia and Africa. However, climate change induced abiotic stresses such as drought, flooding, salinity, heat, and enhanced ultraviolet-B (UV-B) radiation increasingly threaten sustainable rice production. Modern high-yielding rice cultivars possess a narrow genetic base, limiting their adaptability to fluctuating environmental conditions. In contrast, traditional rice landraces represent a rich reservoir of genetic diversity developed through long-term natural and farmer-mediated selection under diverse agro-ecological environments. This review highlights the significance of traditional rice varieties as valuable genetic resources for developing stress-resilient and climate-smart rice genotypes. Traditional cultivars possess unique adaptive traits, including deep root systems for drought tolerance, sodium ion exclusion mechanisms for salinity tolerance, carbohydrate conservation during submergence, maintenance of spikelet fertility under heat stress, and enhanced antioxidant and flavonoid accumulation for UV-B protection. Important stress-tolerance genes from traditional germplasm, such as the SUB1 locus from the flood-tolerant landrace FR13A, have significantly contributed to modern rice improvement programs. The review concludes that traditional rice varieties constitute an indispensable genetic resource for broadening the genetic base of rice breeding programs and developing climate-smart rice cultivars capable of sustaining productivity and ensuring long-term food security under changing climatic conditions.

Keywords Traditional rice, Genetic diversity, Abiotic stress tolerance, Climate-smart breeding, Food security.

INTRODUCTION

Rice (*Oryza sati*va L.) is the cornerstone of global food security, particularly across Asia, Africa, and parts of Latin America. As a primary staple for more than half of the world's population, rice contributes nearly one-fifth of global caloric intake and serves as a direct source of energy, protein, vitamins, and micronutrients for billions of people. Unlike maize and wheat, which are largely diverted to feed, fuel,

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and industrial uses, rice is predominantly consumed directly by humans, making its production stability intimately connected to household food availability and socio-economic resilience. According to the Food and Agriculture Organization (2022), global crop genetic diversity has declined significantly due to the widespread replacement of traditional varieties with uniform modern cultivars. Such genetic erosion diminishes the reservoir of rare alleles required for future crop adaptation. Climate change further amplifies this vulnerability. The Intergovernmental Panel on Climate Change (IPCC 2023) reports increasing frequency and intensity of extreme climatic events, including prolonged droughts, flash floods, heat waves, salinity intrusion in coastal areas, and enhanced ultraviolet-B (UV-B) radiation. Rice, being highly sensitive to environmental fluctuations during reproductive stages, is particularly susceptible to these stresses. For example, drought stress during flowering can reduce spikelet fertility and grain filling, while elevated temperatures during anthesis may cause pollen sterility and significant yield losses (Jagadish *et al.* 2015). Similarly, submergence due to erratic rainfall disrupts oxygen availability and energy metabolism, leading to severe crop damage. Salinity stress impairs ionic balance and photosynthesis (Munns and Tester 2008), whereas UV-B radiation damages DNA, proteins, and photosynthetic machinery, triggering oxidative stress (Hideg *et al.* 2013).

In this context, traditional rice varieties often referred to as landraces or indigenous cultivars gain renewed scientific importance. These varieties evolved over centuries under diverse agro-ecological conditions without intensive chemical inputs or centralized breeding programs. Farmers maintained and selected these genotypes based on resilience, grain quality, cultural preference, and adaptability rather than solely on yield potential. As a result, traditional rice populations accumulated extensive morphological, physiological, and biochemical variation. They exhibit traits such as deep and extensive root systems, flexible flowering time, osmotic adjustment capacity, enhanced antioxidant activity, and efficient hormonal regulation under stress (Elankumaran *et al.* 2026). Traditional rice diversity represents not only phenotypic variation but also hidden molecular richness. Advances in genomics have revealed that landraces harbor unique alleles absent or rare in elite cultivars. These alleles regulate quantitative traits associated with stress signalling, reactive oxygen species (ROS) scavenging, membrane stability, carbohydrate metabolism, and hormonal cross-talk. Unlike single-gene resistance mechanisms, many adaptive traits in traditional rice are polygenic, providing durable and broad-spectrum resilience. The discovery of the SUB1A gene from the flood-tolerant landrace FR13A demonstrated how a single traditional genotype could revolutionize breeding strategies for submergence tolerance (Xu *et al.* 2006; Chakraborty *et al.* 2026). Similar examples exist for drought, salinity, and heat tolerance, reinforcing the value of landraces as dynamic genetic reservoirs. Beyond stress tolerance, traditional rice contributes to nutritional and ecological sustainability. Pigmented rice varieties rich in anthocyanins and phenolic compounds not only provide antioxidant benefits for human health but also enhance plant protection against UV-B radiation and oxidative stress (Oliveira *et al.* 2026). Moreover, many landraces are adapted to low-input systems, demonstrating efficient nutrient use and reduced dependency on synthetic fertilizers. Such traits align with the principles of climate-smart agriculture, which emphasize productivity, resilience, and environmental sustainability. Despite their immense value, traditional rice varieties are rapidly disappearing due to modernization, urbanization, and market preference for uniform grains. The loss of these landraces represents an irreversible erosion of evolutionary heritage and adaptive potential. Conservation strategies both in situ through farmer cultivation and ex situ through gene banks are therefore essential. However, conservation alone is insufficient; systematic characterization and integration of traditional germplasm into modern breeding pipelines are required to translate genetic diversity into tangible agricultural benefits. Modern breeding tools, including marker-assisted selection, genomic selection, high-throughput phenotyping, and gene-editing technologies such as CRISPR/Cas systems, provide unprecedented opportunities to harness traditional rice diversity efficiently. By combining ancient allelic richness with advanced genomic precision, breeders can develop multi-stress tolerant, high-yielding cultivars suited for future climates. In summary, the challenge of sustaining rice production under climate change necessitates a paradigm shift from reliance on narrow genetic pools to strategic utilization of traditional germplasm. Traditional rice varieties embody centuries of evolutionary adaptation and represent a critical foundation for developing climate-resilient and food-secure agricultural systems. Understanding their genetic architecture, physiological responses, and molecular mechanisms is therefore not merely an academic exercise but a strategic imperative for global food security.

Genetic diversity in traditional rice

Genetic diversity is the biological foundation that sustains crop evolution, adaptation, and long-term productivity. In cultivated rice, *Oryza sativa* L., traditional landraces represent one of the richest repositories of naturally evolved genetic variation. These landraces were shaped over centuries through continuous interaction between environmental pressures and farmer-mediated selection. Unlike modern high-yielding varieties that were developed under controlled breeding programs using a limited number of elite parents, traditional rice varieties evolved under diverse agro-ecological conditions including drought-prone uplands, flood-affected lowlands, saline coastal belts, and temperature-stressed tropical ecosystems. This prolonged exposure to heterogeneous environments resulted in the accumulation of diverse allelic combinations conferring adaptive resilience.

Evolutionary basis of genetic diversity

The diversity observed in traditional rice is the outcome of two complementary processes: natural selection and artificial selection by farmers. Natural selection allowed plants with superior stress-adaptive traits to survive and reproduce under challenging environments. Concurrently, farmers consciously selected seeds from plants that exhibited desirable agronomic traits such as resilience, grain quality, taste, and storage ability. This dual selection mechanism fostered the retention of rare and adaptive alleles within local populations. Recent genomic studies have confirmed that traditional rice landraces harbor unique alleles absent or significantly underrepresented in modern cultivars (Elankumaran *et al.* 2026). These alleles are associated with traits such as root system architecture, flowering time plasticity, osmotic adjustment, antioxidant metabolism, and stress-responsive hormonal regulation. Because many of these traits are quantitatively inherited, they are controlled by multiple genes acting in coordination, thereby providing stable and durable tolerance under variable environmental conditions.

Morphological and structural diversity

Traditional rice varieties exhibit striking morphological variability. Plant height may range from semi-dwarf to tall (>180 cm) types. Tall varieties are particularly advantageous in flood-prone areas, where stem elongation allows plants to survive partial submergence. Conversely, upland varieties often develop deeper and more extensive root systems that enhance water extraction during drought. Variation is also evident in leaf morphology, tillering pattern, panicle architecture, grain size, and pigmentation. Pigmented rice varieties, including red and black types, are rich in anthocyanins and phenolic compounds. These secondary metabolites not only improve nutritional value but also contribute to oxidative stress tolerance by scavenging reactive oxygen species (ROS) generated under environmental stress (Oliveira *et al.* 2026). Thus, morphological diversity in traditional rice reflects deeper biochemical and molecular heterogeneity.

Physiological and biochemical adaptations

Traditional rice landraces frequently demonstrate enhanced physiological flexibility compared to elite cultivars. Under drought conditions, many landraces exhibit efficient stomatal regulation mediated by abscisic acid (ABA), thereby reducing transpirational water loss while maintaining photosynthetic activity. Osmotic adjustment through the accumulation of compatible solutes such as proline and soluble sugars helps maintain cell turgor and enzyme functionality. Under salinity stress, traditional varieties may exhibit improved sodium exclusion mechanisms and better potassium retention, maintaining ionic homeostasis essential for metabolic stability (Munns and Tester 2008). During submergence, certain landraces conserve carbohydrates and suppress excessive elongation growth, preventing energy depletion. The identification of the SUB1A gene from a traditional landrace (Xu *et al.* 2006) demonstrated how a single adaptive allele can significantly enhance flood tolerance when introgressed into elite varieties (Chakraborty *et al.* 2026). Oxidative stress management is another critical feature of traditional rice diversity. Environmental stresses such as heat, drought, salinity, and UV-B radiation induce ROS accumulation, which can damage lipids, proteins, and nucleic acids. Traditional rice genotypes often exhibit higher activity of antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), and peroxidases, along with elevated levels of flavonoids and phenolic antioxidants (Hideg *et al.* 2013). This robust antioxidant network enhances cellular protection and stress recovery.

Molecular and hormonal regulation

At the molecular level, genetic diversity in traditional rice is reflected in variations in stress-responsive transcription factors, signalling pathways, and hormone biosynthesis genes. Allelic diversity influencing ABA, gibberellins (GA), cytokinins, and ethylene signalling contributes to flexible developmental responses under stress. For example, drought-adapted landraces may show stronger ABA-mediated stomatal closure, while flood-tolerant types regulate ethylene-responsive pathways to control elongation growth. Advances in genome-wide association studies (GWAS) and quantitative trait loci (QTL) mapping have revealed that many adaptive traits in traditional rice are polygenic, involving complex gene networks rather than single major genes (Elankumaran *et al.* 2026). This polygenic architecture enhances resilience by providing multiple layers of protection against environmental perturbations.

Genetic erosion and its implications

Despite their immense value, traditional rice varieties have been progressively replaced by uniform high-yielding cultivars. The Food and Agriculture Organization (2022) reports that global agricultural systems have experienced significant genetic erosion over the past century. Genetic erosion refers to the loss of allelic diversity within crop populations, resulting in a narrower genetic base and reduced adaptive capacity. The consequences of genetic erosion are particularly concerning under climate change scenarios. Increasing frequency of extreme weather events, as highlighted by the Intergovernmental Panel on Climate Change (IPCC 2023), demands crops with high phenotypic plasticity and stress tolerance. Without the diverse alleles present in traditional germplasm, breeding programs may struggle to respond effectively to emerging environmental challenges.

Importance for future breeding

Traditional rice diversity provides critical raw material for modern breeding strategies. Marker-assisted selection (Collard and Mackill 2008), genomic selection, and gene-editing approaches such as CRISPR/Cas systems (Dash *et al*. 2025) rely on identifying and utilizing beneficial alleles from diverse germplasm sources. By integrating traditional landraces into breeding pipelines, it is possible to broaden the genetic base of modern varieties while maintaining yield stability.

Role of traditional rice in abiotic stress tolerance

Submergence and flood tolerance

Flooding is one of the most destructive stresses in rice-growing regions. Flash floods can completely submerge rice plants, causing oxygen deficiency and energy starvation. Certain traditional rice varieties can survive complete submergence for 10–14 days. These varieties suppress elongation growth during flooding and conserve carbohydrates (Fig.1). The most famous example is the traditional variety FR13A, which led to the identification of the SUB1 gene responsible for flood tolerance (Xu *et al.* 2006). Introgression of the SUB1 gene into popular rice varieties has significantly reduced yield loss in flood-prone areas (Chakraborty *et al.* 2026).

Drought tolerance

Traditional rice cultivars possess diverse adaptive mechanisms that enable them to tolerate drought stress more effectively than many modern cultivars. These landraces often develop deeper root systems,

Fig. 1. Submergence Tolerance Rice Cultivars in Hirakud Dam, Odisha, India

maintain better water-use efficiency, and exhibit improved osmotic adjustment under limited water conditions, which helps sustain growth and productivity during drought stress (Zargar *et al.* 2026, Sandhu and Kumar 2017).

In addition, traditional rice cultivars retain higher chlorophyll content, enhanced antioxidant defense activity, and delayed leaf senescence under drought stress, thereby minimizing oxidative damage and maintaining photosynthetic efficiency (Swapna and Shylaraj 2017). Their wide genetic diversity provides valuable drought-responsive genes that can be utilized in climate-resilient rice breeding programs aimed at improving stress tolerance and yield stability (Fig. 2.) (Naing *et al*. 2026).

Heat stress tolerance

High temperature stress, particularly during anthesis, causes pollen sterility and yield reduction. Traditional rice varieties adapted to hot environments often maintain higher spikelet fertility under heat stress. Elevated temperatures adversely affect seed germination, vegetative growth, tiller development, panicle initiation, flowering, and grain filling, leading to reduced pollen viability, impaired seed setting, lower yield, and deterioration of grain quality. The severity of heat stress varies across growth stages, with reproductive stages being particularly sensitive

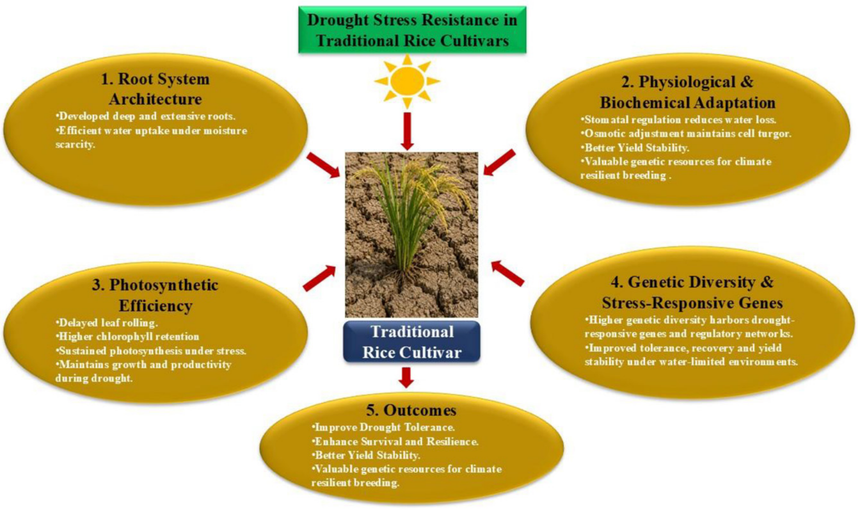

Fig. 2 Schematic illustration of morphological, physiological, biochemical, and genetic mechanisms contributing to drought stress resistance in traditional rice cultivars

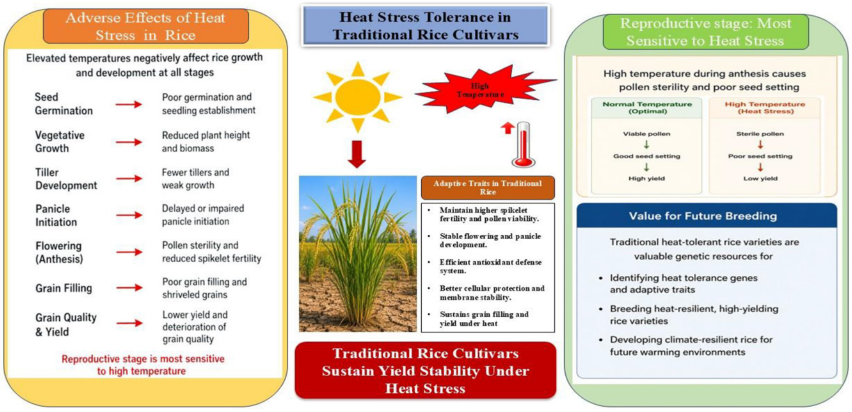

Fig. 3. Heat stress in different growth stage of rice cultivar.

to high-temperature conditions (Fig.3). These traits are valuable for breeding heat-resilient rice varieties suitable for future warming climates (Jagadish *et al.* 2015).

Salinity tolerance

Salt stress induces osmotic and ionic imbalance, which activates stress perception pathways involving Ca^{2+} signalling, abscisic acid (ABA), and reactive oxygen species (ROS). To maintain growth and yield stability, salt-tolerant rice cultivars employ adaptive mechanisms such as Na^+ exclusion, vacuolar ion sequestration, enhanced antioxidant defense (SOD, CAT, APX, POD), and osmotic adjustment through proline and osmolyte accumulation. Several traditional rice varieties tolerate high salinity by: Excluding sodium ions, maintaining potassium balance, Producing Osmo protectants such as proline (Fig. 4). Such varieties serve as important donors for salinity-tolerant breeding programs (Munns and Tester 2008).

UV-B and oxidative stress tolerance

Increased UV-B radiation damages DNA, proteins, and photosynthetic machinery. Traditional rice varieties often contain higher concentrations of flavonoids and phenolic compounds that absorb UV-B radiation

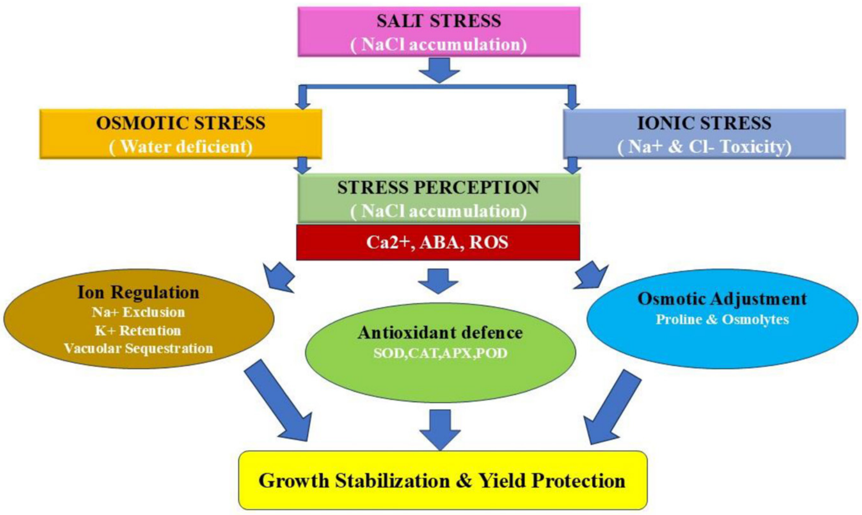

Fig. 4. Defence mechanism of rice against salt stress.

Fig. 5. Morphological diversity among cultivated, traditional, and wild rice germplasm including high-yielding rice, traditional landraces, and wild rice species used for genetic improvement and stress-resilience studies.

(Zhang *et al.* 2025). These compounds also act as antioxidants, protecting plants from oxidative stress. Studies have shown that traditional rice exhibits better UV-B tolerance compared to modern cultivars (Hideg *et al.* 2013).

Traditional rice in climate-smart breeding

Traditional rice germplasm serves as an important source of stress-resilient genes for climate-smart rice breeding programs. The incorporation of adaptive traits from traditional landraces into modern cultivars enhances tolerance to multiple abiotic stresses, improves yield stability, and supports sustainable rice production under changing climatic conditions without significantly compromising productivity (Fig.5) (Elankumaran *et al.* 2026).

Diversity and climate stress-tolerant traits of traditional rice landraces of odisha

Traditional rice landraces of Odisha possess wide genetic diversity and exhibit adaptation to diverse agro-ecological conditions. These cultivars harbor important stress-resilient traits such as drought, salinity, submergence, heat, and UV-B tolerance, making them valuable genetic resources for climate-smart rice breeding. The distribution of tolerant landraces across upland, coastal, rainfed, and lowland ecosystems highlights their ecological adaptability and potential role in sustainable agriculture under changing climatic conditions. A total of 50 traditional cultivars were categorized based on their adaptation to diverse agro-ecological conditions such as upland, rainfed, lowland, coastal, tribal upland, and marginal soil ecosystems. Among the recorded accessions, drought tolerance was the most predominant trait, particularly in upland and rainfed cultivars including Koraput Kalajeera, Basubhoga, Dangarbasumati, Kalahandi Local, and Muktabali. Several landraces also exhibited tolerance to other climate-related stresses. Coastal and lowland cultivars such as Patnai, Matta, and Padmakeshari were associated with submergence tolerance, while Ganjam Local and Nalabainsi showed salinity tolerance under coastal ecosystems. Certain traditional varieties including Navara, Rakthashali, and Kumkumshali demonstrated combined tolerance to heat, drought, and UV-B stress, indicating their potential utility in climate-resilient breeding programs. Overall highlights the rich genetic diversity of Odisha traditional rice germplasm as an important reservoir of adaptive traits for sustainable rice improvement under changing climatic conditions (Table 1).

Critical role in development of climate-smart genotypes

Importance of traditional rice germplasm

Traditional rice landraces possess extensive genetic diversity developed through long-term adaptation to diverse environmental conditions. These landraces contain valuable stress-responsive genes that can improve resilience against drought, flooding, salinity, heat, UV-B radiation, and oxidative stress. Their broad adaptive potential makes them important genetic resources for climate-smart rice breeding programs (Elankumaran *et al.* 2026).

Contribution to submergence tolerance

One of the most significant achievements in cli-

Table 1. Traditional Rice Landraces of Odisha and Associated multiple Stress Tolerance.

Sl. No.	Variety name	District / Region Odisha	Ecosystem type	Major stress Tolerance
1	Koraput Kalajeera	Koraput	Upland	Drought
2	Kalajeera (local types)	Koraput, Rayagada	Upland	Drought
3	Basubhoga	Jeypore tract	Upland	Drought
4	Dangarbasumati	Koraput	Upland	Drought
5	Tulasiganthi	Southern Odisha	Upland	Drought
6	Kalachampa	Keonjhar	Rainfed upland	Drought
7	Kullakar (local type)	Southern Odisha	Upland	Drought
8	Kalahandi Local	Kalahandi	Rainfed	Drought
9	Sambalpur Local	Sambalpur	Rainfed	Drought
10	Jharsuguda Local	Jharsuguda	Rainfed	Drought
11	Malkangiri Local	Malkangiri	Tribal upland	Drought
12	Patnai (local types)	Coastal Odisha	Lowland	Submergence
13	Ganjam Local	Ganjam	Coastal	Salinity
14	Matta (local)	Coastal districts	Lowland	Submergence
15	Kalajiri	Koraput	Upland	Drought
16	Navara (local)	Koraput	Upland	Heat/Drought
17	Rakthashali	Southern Odisha	Upland	UV-B / Antioxidant
18	Kumkumshali	Tribal Odisha	Upland	UV-B / Oxidative
19	Kalamalli	Southern Odisha	Marginal soil	Multi-stress
20	Kanakchudi	Southern Odisha	Upland	Drought
21	Muktabali	Tribal belts	Upland	Drought
22	Kalabat	Odisha	Rainfed	Drought
23	Tulasibasa	Odisha	Low input	Drought
24	Pimpudibasa	Odisha	Rainfed	Drought
25	Padmakeshari	Odisha	Lowland	Submergence
26	Balami	Odisha	Rainfed	Drought
27	Nalabainsi	Coastal Odisha	Lowland	Salinity
28	Khandagiri Local	Khordha	Coastal fringe	Salinity
29	Dudheswar (local)	Odisha	Rainfed	Drought
30	Gopalbhog	Odisha	Rainfed	Drought
31	Kataribhog	Coastal Odisha	Lowland	Salinity
32	Malshira	Coastal Odisha	Delta region	Salinity
33	Binni	Coastal Odisha	Delta	Salinity
34	Korpali Local	Koraput	Upland	Drought
35	Tikichudi	Southern Odisha	Upland	Multi-stress
36	Bahuroopi	Odisha	Rainfed	Multi-stress
37	Kanchana (local)	Odisha	Rainfed	Drought
38	Danteshwari (local)	Odisha	Rainfed	Drought
39	Mahamaya (local)	Odisha	Rainfed	Drought
40	Kalachudi	Tribal Odisha	Upland	Drought
41	Koraput Black Rice	Koraput	Upland	UV-B / Antioxidant
42	Odisha Red Rice (local)	Southern Odisha	Upland	Oxidative stress
43	Koraput Aromatic Local	Koraput	Upland	Drought
44	Rayagada Local	Rayagada	Upland	Drought
45	Nabarangpur Local	Nabarangpur	Rainfed	Drought
46	Kendujhar Local	Keonjhar	Rainfed	Drought
47	Mayurbhanj Local	Mayurbhanj	Rainfed	Drought
48	Balasore Coastal Local	Balasore	Coastal	Salinity
49	Puri Coastal Local	Puri	Coastal	Salinity
50	Jagatsinghpur Local	Jagatsinghpur	Coastal	Salinity

mate-resilient rice breeding is the identification of the SUB1A gene from the traditional flood-tolerant rice landrace FR13A. This gene enables rice plants to survive prolonged submergence by conserving carbohydrates and suppressing excessive elongation growth. Introgression of SUB1A into elite rice cultivars has significantly improved productivity in flood-prone regions (Xu *et al.* 2006, Chakraborty *et al.* 2026).

Role in drought and salinity tolerance

Traditional upland rice cultivars possess adaptive traits such as deep root systems, osmotic adjustment, and efficient water-use efficiency that enhance drought tolerance. Similarly, coastal rice landraces exhibit salinity tolerance through sodium ion exclusion, potassium retention, and osmo-protectant accumulation. These traits are highly valuable for breeding stress-resilient rice cultivars suitable for water-limited and salt-affected ecosystems (Munns and Tester 2008).

UV-B protection and antioxidant defense

Pigmented traditional rice varieties rich in anthocyanins, flavonoids, and phenolic compounds provide enhanced protection against UV-B radiation and oxidative stress. These bioactive compounds function as antioxidants and reduce cellular damage caused by reactive oxygen species (ROS), thereby improving stress tolerance and nutritional quality (Hideg *et al.* 2013, Oliveira *et al.* 2026).

Integration with modern breeding technologies

Advanced breeding tools such as marker-assisted selection, genomic selection, and CRISPR/Cas-mediated gene editing facilitate the efficient transfer of stress-tolerance genes from traditional rice into elite cultivars. Integration of traditional germplasm with modern genomic technologies can accelerate the development of multi-stress tolerant climate-smart rice genotypes capable of sustaining productivity under changing climatic conditions (Dash *et al.* 2025).

DISCUSSION

Traditional rice landraces represent a unique and irreplaceable source of genetic diversity for future rice improvement under changing climatic conditions. The present review demonstrates that indigenous rice cultivars possess remarkable morphological, physiological, biochemical, and molecular variability that contributes significantly to abiotic stress tolerance and climate resilience. Modern rice breeding programs have achieved substantial yield improvements through the development of semi-dwarf and fertilizer-responsive cultivars; however, these advances have also narrowed the genetic base of cultivated rice. Such genetic uniformity increases vulnerability to drought, flooding, salinity, heat stress, and ultraviolet-B (UV-B) radiation, which are becoming increasingly severe due to global climate change (IPCC 2023). In this context, traditional rice varieties provide an essential reservoir of adaptive alleles that can enhance resilience and long-term sustainability of rice production systems.

The extensive diversity observed in traditional rice germplasm is largely the result of prolonged natural selection and farmer-mediated selection under diverse agro-ecological environments. Unlike modern high-yielding cultivars developed under controlled breeding conditions, traditional landraces evolved in drought-prone uplands, flood-affected lowlands, saline coastal ecosystems, and heat-stressed tropical environments. Consequently, these landraces accumulated adaptive traits associated with stress tolerance, phenotypic plasticity, and environmental fitness. Elankumaran *et al*. 2026) reported that traditional rice cultivars harbor unique alleles regulating root architecture, osmotic adjustment, antioxidant metabolism, and hormonal signalling pathways, many of which are absent or underrepresented in elite cultivars. These findings support the idea that traditional rice diversity forms the biological foundation for future climate-resilient breeding programs. Among the various abiotic stresses discussed in this review, submergence tolerance represents one of the most successful examples of utilizing traditional rice germplasm in modern crop improvement. Flooding severely disrupts oxygen availability and energy metabolism in rice plants, leading to substantial yield losses in lowland ecosystems. Certain traditional rice cultivars survive prolonged submergence by suppressing excessive elongation growth and conserving carbohydrate reserves. The identification of the SUB1A gene from the traditional landrace FR13A revolutionized breeding strategies for flood tolerance (Xu *et al,* 2006). Introgression of this gene into high-yielding rice varieties has significantly improved productivity in flood-prone regions (Chakraborty *et al.* 2026). This example demonstrates how traditional germplasm can provide practical genetic solutions to climate-related agricultural challenges.

Drought stress remains another major limitation to rice production, particularly in rainfed and upland ecosystems. The review indicates that traditional rice cultivars and wild relatives such as *Oryza nivara* exhibit superior drought-adaptive mechanisms including deeper root systems, efficient stomatal regulation, osmotic adjustment, and improved water-use efficiency. These adaptive responses enable maintenance of physiological activity under water-deficit conditions and improve survival during prolonged drought periods. The ecological distinction between O. nivara and *O. rufipogon* further reflects evolutionary specialization toward dry and deep-water habitats, respectively. Such genetic diversity provides valuable opportunities for breeding drought-resilient rice cultivars. Similar observations were reported by Kuru *et al.* 2021, who highlighted the superior physiological performance of traditional rice under stress environments. Heat stress tolerance is increasingly important under projected global warming scenarios. High temperatures during reproductive stages adversely affect pollen viability, spikelet fertility, grain filling, and overall yield stability. The present review suggests that traditional rice varieties adapted to warmer agro-climatic regions maintain better reproductive performance under elevated temperatures. Jagadish *et al*. (2015) also emphasized that reproductive-stage heat tolerance is one of the critical determinants of future rice productivity. Therefore, heat-tolerant traditional rice cultivars represent important donor materials for developing climate-smart rice varieties capable of withstanding rising temperatures. Salinity stress is another growing concern, particularly in coastal rice-growing areas affected by sea-water intrusion and irrigation-related salt accumulation. Traditional rice landraces possess several physiological mechanisms that contribute to salinity tolerance, including sodium ion exclusion, potassium retention, osmotic adjustment, and antioxidant defense. Maintenance of ionic balance and membrane stability under saline conditions enables these cultivars to survive and maintain growth under high salt concentrations. Munns and Tester (2008) similarly identified ion homeostasis as a major mechanism governing salinity tolerance in crop plants. The utilization of salinity-tolerant traditional rice in breeding programs could therefore improve rice productivity in salt-affected ecosystems.

The review also highlights the importance of pigmented traditional rice varieties in UV-B and oxidative stress tolerance. Increased UV-B radiation damages cellular components including DNA, proteins, lipids, and photosynthetic machinery through excessive production of reactive oxygen species (ROS). Traditional red and black rice cultivars contain elevated levels of anthocyanins, flavonoids, and phenolic compounds that function as antioxidants and UV-B absorbers. These compounds enhance cellular protection against oxidative damage while simultaneously improving nutritional quality. Similar findings were reported by Hideg *et al.* (2013) and Oliveira *et al.* (2026), who demonstrated the important role of antioxidant systems in mitigating stress-induced oxidative injury. Thus, traditional rice varieties contribute not only to agronomic resilience but also to nutritional and health security. Another important aspect discussed in this review is the integration of traditional rice diversity with modern molecular breeding technologies. Conventional breeding methods alone are often time-consuming when dealing with complex quantitative traits such as drought and heat tolerance. Advanced approaches including marker-assisted selection, genomic selection, genome-wide association studies, and CRISPR/Cas-mediated gene editing now provide efficient tools for identifying and transferring beneficial alleles from traditional germplasm into elite cultivars (Collard and Mackill 2008, Dash *et al.* 2025). These technologies can accelerate the development of climate-smart rice genotypes capable of tolerating multiple environmental stresses while maintaining productivity. However, many stress-adaptive traits in traditional rice are polygenic and regulated through complex gene networks and hormonal interactions. Therefore, future breeding programs should focus on pyramiding multiple adaptive traits to achieve durable and broad-spectrum resilience. Despite their immense breeding value, traditional rice landraces are rapidly disappearing due to modernization, urbanization, and replacement by uniform high-yielding cultivars. This ongoing genetic erosion threatens the availability of rare adaptive alleles that may become essential under future climate scenarios. Conservation of traditional rice through ex situ gene banks, in situ cultivation, and participatory breeding approaches is therefore urgently required. Strengthening farmer participation and policy support for conservation programs will help maintain these valuable genetic resources for future utilization.

CONCLUSION

Traditional rice landraces constitute an invaluable genetic reservoir for developing climate-resilient and sustainable rice production systems under changing global environmental conditions. The present review clearly demonstrates that indigenous rice cultivars possess extensive morphological, physiological, biochemical, and molecular diversity that enables adaptation to multiple abiotic stresses including drought, submergence, salinity, heat, UV-B radiation, and oxidative stress. Unlike modern high-yielding cultivars with a narrow genetic base, traditional rice varieties evolved under diverse agro-ecological conditions through long-term natural and farmer-mediated selection, resulting in the accumulation of unique adaptive alleles and stress-responsive traits. The evidence presented throughout this manuscript highlights that traditional rice varieties are not merely heritage crops but strategic biological resources for future climate-smart breeding programs. Traits such as deep root systems, osmotic adjustment, efficient antioxidant defense, sodium ion exclusion, carbohydrate conservation, and maintenance of reproductive stability under stress conditions provide valuable mechanisms for improving resilience in modern rice cultivars. The successful identification and utilization of the SUB1A gene from the traditional flood-tolerant landrace FR13A further illustrates the immense breeding potential of indigenous germplasm for enhancing stress tolerance in elite rice varieties (Xu *et al.* 2006; Chakraborty *et al.* 2026). Similarly, traditional upland, coastal, and pigmented rice cultivars represent important donor sources for drought, salinity, heat, and UV-B tolerance.

The review also emphasizes that future rice improvement programs must move beyond reliance on narrow genetic pools and adopt integrated approaches combining traditional germplasm with advanced molecular breeding technologies. Marker-assisted selection, genomic selection, genome-wide association studies, and CRISPR/Cas-mediated gene editing provide powerful tools for identifying and transferring beneficial alleles from traditional rice into high-yielding cultivars. Since many stress-adaptive traits are polygenic and regulated through complex molecular networks, breeding strategies should focus on pyramiding multiple tolerance traits to achieve durable and broad-spectrum climate resilience. Despite their immense agricultural importance, traditional rice landraces are rapidly disappearing due to modernization, urbanization, and replacement by uniform commercial cultivars. This genetic erosion threatens the availability of rare adaptive genes essential for future crop improvement. Therefore, both ex situ conservation through gene banks and in situ conservation through farmer participation and on-farm cultivation are urgently required. Participatory breeding, policy support, and systematic characterization of traditional germplasm will further strengthen sustainable utilization of these genetic resources. In conclusion, traditional rice germplasm provides a critical foundation for the development of next-generation climate-smart rice genotypes capable of maintaining productivity, nutritional quality, and environmental sustainability under future climate scenarios. Conservation, scientific utilization, and integration of traditional rice diversity into modern breeding pipelines will play a decisive role in ensuring long-term food security and sustainable agricultural development worldwide.

AUTHOR CONTRIBUTIONS

PKS- Concept, manuscript writing, review and correspondence, PMB- Data collection.

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