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Research Article

Exploring traditional rice germplasm in Sri Lanka: Morphological diversity, stress adaptation, nutritional value, and future breeding potential

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Abstract

Sri Lankan traditional rice varieties represent a valuable genetic resource characterized by substantial diversity in morphological, agronomic, adaptive, and nutritional traits. This study synthesizes the key variations observed among traditional germplasm with emphasis on vegetative growth, yield performance, stress tolerance, and nutritional quality to highlight their potential for sustainable rice improvement. Considerable morphological variability is evident in vegetative traits such as plant height, tillering ability, leaf number, and biomass production. Tall and vigorous varieties such as *Ma Wee* and *Hodarawala* exhibit high vegetative growth, while varieties such as *Kaluheenati* and *Kuruluthuda* demonstrate moderate plant height with efficient tillering. Variation in grain morphology, including size, shape, and pericarp color, further reflects the broad phenotypic diversity present in traditional germplasm. Significant differences are also observed in yield characteristics and agronomic performance. Varieties such as *Ma Wee* and *Sudu Heenati* show superior panicle length, grain number, and grain filling under favorable conditions, indicating high yield potential. In contrast, *Pachchaperumal* and *Kuruluthuda* exhibit moderate but stable yields across seasons, highlighting their reliability under variable field conditions. Traditional rice varieties demonstrate strong environmental stress adaptability, making them suitable for low-input and climate-vulnerable environments. *Kaluheenati*, *Pachchaperumal* and *Niyan Wee* are well adapted to drought and nutrient-poor soils, while *Ma Wee* performs well under waterlogged or flood-prone conditions. In addition to agronomic advantages, traditional varieties provide important nutritional and health benefits. Pigmented rice types such as *Kaluheenati*, *Pachchaperumal*, and *Madathawalu* are rich in antioxidants, iron, and dietary fiber, while aromatic varieties like *Suwandel* are preferred for their superior grain quality and consumer acceptability. The wide variability observed in vegetative growth, yield traits, stress tolerance, and nutritional composition highlights the significant potential of Sri Lankan traditional rice for breeding programs, conservation efforts, and sustainable agriculture under changing climatic conditions.

Keywords: Sri Lankan traditional rice, Germplasm diversity, Stress adaptation, Nutritional value, Sustainable breeding, Climate resilience

Introduction

Rice (*Oryza sativa* L.) has been the principal staple crop in Sri Lanka for centuries, underpinning food security, rural livelihoods, and agrarian culture (Somaratne & Weerakoon, 2020). The rice crop provides a major proportion of daily caloric and protein intake for the population, particularly in rural households that depend on rice for sustenance and income (Fukagawa & Ziska, 2019). Traditional agro-ecosystems in Sri Lanka historically revolved around paddy cultivation, with rice grown across diverse ecological zones from wet lowlands to drought-prone uplands (Chithranayana & Punyawardena, 2008). Sri Lankan paddy fields occupy a substantial portion of the national agricultural landscape and have shaped village life, labor patterns, and cultural practices connected to seasonal cycles and festivals (Abeywardana *et al.,* 2019).

Beyond its role as a food source, traditional rice varieties maintained by farmers represent a legacy of environmental adaptation and cultural preferences. These varieties were selected over generations for traits such as taste, grain quality, maturity time, and stress resilience. Collections at national gene banks, such as the Plant Genetic Resources Centre (PGRC) in Peradeniya, conserve thousands of these local accessions, reflecting the crop's historical breadth across agro-ecological contexts (Somaratne & Weerakoon, 2020). Studies using molecular markers have demonstrated substantial genetic diversity among Sri Lankan traditional varieties, with high levels of allelic richness and heterozygosity relative to modern improved lines. This diversity is valuable not only for preserving biodiversity but also as a genetic reservoir for future breeding initiatives targeting complex traits like stress tolerance and nutritional quality (Fernando *et al.,* 2015; Weerakoon & Somaratne, 2021).

Rice cultivation in Sri Lanka now faces multiple agronomic challenges driven by climate change and environmental degradation. Climatic variability including increased temperature, irregular rainfall, prolonged drought, and episodic flooding has been linked to fluctuations and declines in rice yields, threatening rural food security (Sathischandra *et al.,* 2014). The productivity of Sri Lankan rice systems is increasingly threatened by soil-related constraints, most notably coastal salinization resulting from global sea-level rise. This is compounded by severe water shortages during sensitive growth stages, which significantly worsen yield instability. Comprehensive climate impact assessments identify rising temperatures and altered rainfall patterns as primary environmental stressors; these not only lower crop yields but also disrupt the ecological balance, leading to a stronger presence of plant diseases and more frequent pest outbreaks within these farming landscapes (Ratnayake *et al.,* 2023). Moreover, socioeconomic stresses such as rising input costs and policy

disruptions have compounded agronomic vulnerability for smallholder rice farmers (Jayarathne, 2023).

Within this context, traditional rice germplasm offers critical adaptive potential. Many landraces display resilience to abiotic stresses such as drought and heat for example, drought-tolerance screening has identified accessions like *Suwandal* and *Kirimurunga* with superior performance under water deficit (Madurangi *et al.,* 2012). The inherent variability in stress responses and phenology found among traditional accessions suggests that valuable alleles for resilience traits are present and can be leveraged in breeding programmes that aim to mitigate the impacts of climate change and environmental stresses (Munasinghe & Price, 2016).

Despite often lower yields under high-input conditions compared with modern cultivars, traditional rice varieties frequently excel in adaptability and grain quality traits valued by consumers and local markets (Sinthuja *et al.,* 2021). In addition, these landraces often possess unique nutritional profiles including higher concentrations of micronutrients and bioactive compounds that are increasingly recognized for their health benefits. Consequently, traditional germplasm is a strategic resource for breeding initiatives that strive not only to maintain or improve yield stability, but also to enhance nutritional value and ecological sustainability (Samaranayake *et al.,* 2017).

The objective of this review is to synthesize existing knowledge on Sri Lankan traditional rice germplasm with respect to its morphological diversity, agronomic performance, environmental adaptability, and nutritional significance, and to evaluate its potential for inclusion in future rice breeding programmes aimed at fostering resilience and sustainability in the face of global challenges.

Methodology

This review was conducted using literature survey to synthesize existing knowledge on traditional rice germplasm in Sri Lanka, with particular emphasis on morphological diversity, stress adaptation, nutritional characteristics, and their potential for future breeding programs.

Literature search strategy

Relevant scientific publications were identified through comprehensive searches in major academic databases including Google Scholar, Scopus, Web of Science, and ScienceDirect. The search was conducted using combinations of keywords; traditional rice varieties in Sri Lanka, rice landraces, morphological diversity of rice, abiotic and biotic stress tolerance in rice, nutritional composition of traditional rice, and rice genetic resources and breeding potential.

Inclusion and exclusion criteria

Peer-reviewed journal articles, review papers, conference proceedings, institutional reports, and authoritative online resources published primarily between 2000 and 2025 were considered. Studies focusing on Sri Lankan traditional rice varieties, landrace characterization, stress tolerance traits, grain quality, and nutritional properties were included. Publications unrelated to traditional rice and those lacking reliable scientific evidence were excluded.

Data extraction

Relevant information from selected studies was extracted and categorized under four main themes:

1. Morphological and genetic diversity of traditional rice germplasm
2. Adaptation to abiotic and biotic stresses
3. Nutritional and functional properties of traditional rice varieties
4. Potential applications in modern rice breeding programs

The collected literature was critically discussed to identify major research findings and knowledge gaps related to Sri Lankan rice germplasm.

Results

Morphological variation of traditional rice germplasm

Sri Lankan traditional rice varieties exhibit significant morphological diversity, reflecting long-term adaptation to diverse agro-ecological zones and farmer selection practices. Phenotypic traits such as plant height, panicle length, grain size, grain shape, and grain color vary widely among germplasm.

These morphological differences are shaped by both ecological conditions and farmer selection for traits such as taste, yield stability, and stress tolerance. While most rice lands are currently dominated by new improved varieties (NIVs), traditional and older improved varieties continue to be cultivated on smaller scales, particularly in rainfed systems (Somaratne & Weerakoon, 2020). Studies characterizing nearly 700 Sri Lankan rice accessions have confirmed significant morphological and yield variation, reinforcing the diversity of germplasm available for breeding programs (Padukkage *et al.,* 2015; Pushpakumari *et al.,* 2016).

Multiple studies have documented the extensive morphological variation inherent in Sri Lankan traditional rice varieties. Rathnathunga and Geekiyanage (2017) evaluated *Pachchaperumal* and *Suduru Samba* accessions using a combination of morphological traits and days to flowering (DF). The hierarchical cluster analysis identified two major clusters at a rescale distance of 25, which effectively differentiated the varieties. *Pachchaperumal* was characterized by longer grains (0.7–1.1 cm) and light brown to red pericarps, whereas *Suduru Samba* produced smaller grains (0.5–0.6 cm) with off-white pericarps.

Similarly, Wijayawardhana *et al.* (2015) assessed the vegetative traits of 16 rice accessions, including both

traditional and improved varieties. Analysis classified the germplasm into three distinct groups, reinforcing the clear morphological divergence between traditional and improved varieties. Collectively, these findings highlight the significance of morphological markers and phenological traits, such as flowering time, in characterizing the genetic diversity of Sri Lankan rice.

Weerakoon and Somaratne (2021) characterized 100 traditional rice varieties, identifying seven distinct groups based on morphological traits such as lemma palea color, awn color, seedling height, and flag-leaf angle, with molecular analysis confirming high genetic diversity across five major clusters. Suriyagoda *et al.* (2011) reported that morphological traits across both vegetative and reproductive stages effectively classify rice germplasm, revealing significant phenotypic variation that distinguishes traditional from newly improved varieties and reflects a broad genetic base.

Early studies demonstrated that key parameters including days to flowering (DF), plant height (PH), total tiller number (TTN), grains per panicle (GPP), and total panicle weight (TPW) are significantly influenced by the interaction of accession, season, and photoperiod in varieties such as *Ma Wee, Masuran*, and *Kalu Heenati* (Pushpakumari *et al.,* 2017, 2024, 2025a).

A critical finding emerged regarding photoperiod sensitivity; specifically, in a study of 43 *Ma Wee* accessions, only 9 flowered under the short-day signals of the Maha season, proving that flowering in these traditional varieties is strictly environmentally triggered (Pushpakumari *et al.,* 2017). Most recently, regression analyses have been employed to quantify the variety and seasonal determinants of productivity, identifying specific quadratic and linear correlations between DF and yield components like total panicle weight (Pushpakumari *et al.,* 2025b).

These findings highlight a significant genotype-by-environment interaction governing the phenotypic expression of traditional Sri Lankan rice. Specifically, the observed variations in phenology and yield components reflect an evolutionary adaptation to localized environments, while simultaneously defining the seasonal cultivation limits of photoperiod-sensitive accessions

Yield characteristics and agronomic performance of Sri Lankan traditional rice varieties

Yield potential among Sri Lankan traditional rice varieties exhibits significant genetic and phenotypic variation, driven by differences in yield component traits such as effective tiller number, panicle weight, spikelet number, and filled grain percentage. In traditional varieties evaluated under field conditions, grain yield per plant has been shown to correlate positively with these key agronomic traits, indicating their importance in determining yield components

There is a significant yield variability among medicinally important accessions with total panicle weight (up to 24.7 g) and number of grains per panicle (up to 172) varying widely across accessions (Pushpakumari & Geekiyanage, 2014). These results align with broader research on rice variety diversity, which shows that yield-associated traits often exhibit high variance and heritability, providing opportunities for selection and breeding. In other rice germplasm studies outside Sri Lanka, the number of filled grains per panicle and total grain number per panicle were identified as major contributors to yield variation, reinforcing the concept that yield is a multi-trait phenotype controlled by several component characters (Dinesh *et al.,* 2023).

Seasonal and environmental influences on yield

Yield performance in traditional rice is not fixed; it is highly influenced by seasonal environments and photoperiod responses. The interaction between genotype and growing season affects developmental timing, vegetative growth, and ultimately, yield components (Pushpakumari *et al.,* 2021). Although much of the photoperiod-specific research originates from targeted controlled studies, broader rice research shows that temperature, daylength, and seasonal climatic variables influence vegetative development and yield outcomes across diverse germplasm (Rathnathunga *et al.,* 2019).

In multi-season field evaluations conducted in Sri Lanka, significant differences in plant height, tiller number, and effective panicles were observed between the Maha and Yala seasons, suggesting that seasonal variation alters the expression of yield-associated traits (Pushpakumari & Geekiyanage, 2015). Such season-specific responses are consistent with international research on rice varieties from rainfed conditions where differences in solar radiation and water availability affected yield parameters and biological yield (Garcés-Varon & Restrepo-Díaz, 2015). These findings highlight the need to consider eco physiological interactions when assessing yield performance of traditional rice varieties under differing seasonal regimes.

Recent research confirm that yield component traits contribute differently to final grain yield in rice (Suriyagoda *et al.,* 2011) used principal component analysis to show that reproductive characteristics including number of filled grains per panicle, number of tillers per unit area, and hundred-grain weight explained substantial variation in reproductive performance among traditional and improved varieties, and that traditional varieties in particular had broader variation in these traits. This indicates that morphological diversity translates into agronomic adaptability, which is crucial for yield stability across environments.

Comparisons with improved varieties

Comparative evaluations between traditional and improved rice varieties reveal important differences in agronomic performance. Sewwandi *et al.* (2023) compared growth and yield traits of 20 rice varieties (including four traditional and 16 improved) under organic fertilizer management. They found that the traditional variety

Madathawalu performed well in traits such as plant height, panicle length, and total panicle dry weight compared to improved cultivars, suggesting that traditional landraces may outperform modern varieties under low-input systems. Conversely, improved varieties tended to exhibit superior tillering capacity and vegetative vigor, reflecting their breeders' emphasis on maximizing yields under high-input conditions.

The contrasting performance under different management systems highlights the need to consider cultivation context when assessing yield potential. Traditional varieties may offer advantages in organic or low-input systems due to their robust morphological traits and adaptation, while improved varieties contribute yield advantages under conventional agronomic regimes. Integrating traditional diversity into modern breeding frameworks could combine yield potential with stress resilience and adaptability.

Implications for breeding and cultivation

The documented variation in yield and agronomic traits among Sri Lankan traditional rice varieties has several implications for breeding and cultivation:

Diverse selection criteria

Traits such as fertile tiller number, panicle weight, and filled grain percentage which are highly correlated with grain yield can serve as effective selection targets in breeding programs aimed at yield improvement in traditional germplasm (Dinesh *et al.,* 2023).

Seasonal adaptation

Recognizing the influence of seasonal environments on yield components motivates the development of season-specific cultivar recommendations and planting windows that align flowering and grain development with optimal conditions (Amarasingha *et al.,* 2015; Pushpakumari *et al.,* 2021).

Modern breeding techniques

Combining traditional variety traits with modern breeding strategies (e.g., marker-assisted selection) can develop new varieties that maintain high yield while enhancing stress tolerance and adaptability (Marone *et al.,* 2021).

Environmental stress adaptability of Sri Lankan traditional rice varieties

Submergence tolerance

Flooding represents a major constraint to rice cultivation in Sri Lanka, particularly in lowland areas with poor drainage. Increasing rainfall intensity and the expansion of irrigated lowlands have exacerbated this issue, leading to periodic crop losses (Bentota *et al.,* 2010). Globally, the International Rice Research Institute (IRRI) initiated systematic screening for submergence-tolerant rice genotypes in the 1970s. Of over 100,000 accessions maintained at IRRI, fewer than 1,000 were collected from flood-prone regions, with Bangladesh contributing 443 accessions and Sri Lanka contributing 82 (Dwivedi, 1992; Manzanilla *et al.,* 2011).

Two notable submergence-tolerant landraces, *FR13A* and *FR43B*, collected from Odisha (India), have been widely used as donor parents in breeding programs (Mohanty & Khush, 1985). The *SUB1* gene, located on chromosome 9, has been cloned and extensively utilized for marker-assisted breeding, providing quantitative tolerance to complete submergence and enhancing recovery upon submergence (Oladosu *et al.,* 2020; Mackill *et al.,* 2012).

In Sri Lankan germplasm, Magneschi *et al.* (2009) evaluated 23 varieties under simulated anaerobic conditions and found *Bg 94-1* exhibited the longest coleoptiles (13.8 ± 4.5 mm), whereas Bg 250 and Bg 745 had the shortest (1.3 ± 0.5 mm and 2.3 ± 1.6 mm, respectively) after four days of submergence. Hydro-priming experiments with 37 improved and traditional varieties identified *Bg 300, Bg 310,* and *At 308* as moderately tolerant to anaerobic germination under submergence Illangakoon *et al.* (2016). These studies suggest that Sri Lankan traditional rice germplasm contains valuable alleles for submergence tolerance, which can be exploited in breeding programs.

Salinity tolerance

Salinity stress is a significant abiotic constraint in coastal and lowland rice areas, and tolerance varies depending on the developmental stage of the plant (Munns & Tester, 2008). Traditional varieties cultivated in salt-affected areas often exhibit resilience despite disadvantages such as long maturity and low yield (Heenan *et al.,* 1988). The widely used donor is *Pokkali*, known for maintaining low Na^+ accumulation, high K^+ uptake, and Na^+/K^+ homeostasis under saline conditions. The Saltol QTL, identified on chromosome 1 from a *Pokkali × IR29 cross*, regulates ionic balance and has been extensively used in breeding (Ren *et al.,* 2005).

In Sri Lanka, Senanayake *et al.* (2017) reported that *Pokkali* accessions 5557 and Ac 810 were highly tolerant at the germination and seedling stages. Similarly, Thamali *et al.* (2023) confirmed salinity tolerance of *Pokkali* IRRI accessions and noted moderate tolerance in local varieties Bg 359 and Bg 369. Interestingly, survival rates under salinity are influenced by fragrance: non-fragrant varieties such as *Kalu Heenati* (Acc. No. 003989) showed higher survival than fragrant varieties like *Kuruluwee* (Acc. No. 004903) (Wijerathna *et al.,* 2011). Genetic studies on elite indica varieties *At 354* (salt-tolerant) and *Bg 352* (salt-susceptible) revealed high polymorphism in SNPs and QTL regions, providing a foundation for developing salt-tolerant lines suitable for organic agriculture (Abhayawickrama *et al.,* 2020).

Drought tolerance

Drought is a major yield-limiting factor, especially in rainfed systems, and is predicted to intensify under climate change scenarios (Panda *et al.,* 2021). Genetic improvement for drought tolerance is a high-priority research theme, and molecular markers have become a vital tool for identifying QTLs linked to stress resilience (Mishra *et al.,* 2013). Major drought-tolerance QTLs, including *qtl12.1, qtl3.1, qtl1.1, and qtl9.1*, have been mapped and are being integrated into breeding pipelines for high-yielding varieties under water-limited conditions (Vikram *et al.,* 2011).

Screening of 24 Sri Lankan traditional rice accessions at the seedling stage revealed *Suwandel*, *Kirimurunga*, and *Suduru Samba* as drought-tolerant, showing strong recovery after stress periods (Munasinghe *et al.,* 2017). The SSR marker of *RM252* was identified as potential candidate for tracing drought-tolerance traits in landraces (Munasinghe & Price, 2016). Studies of the traditional variety *Niyan Wee* revealed a deep-rooting structure advantageous for drought adaptation, suggesting its use in breeding programs to mitigate the impacts of climate change.

Iron toxicity tolerance

Iron toxicity is a critical abiotic stress in irrigated rice systems, especially under anaerobic conditions where Fe^{2+} concentration rises, causing leaf bronzing, growth reduction, and spikelet sterility (Mahender *et al.,* 2019). Yield losses can reach 100% under severe exposure (Sahrawat, 2005). In Sri Lanka, high iron soils are found in the low-country wet zone (LCWZ) and in districts such as Matara, Galle, Kalutara, and Trincomalee (Siriwardana *et al.,* 2019). Screening of 12 traditional varieties during the 1998 Yala season revealed *Kahatawee, Devareddiri, Sulai,* and *Molligoda* as highly tolerant, whereas varieties such as *Vellaiiankayan, Dikwee*, and *Murungakayan* were susceptible (Bentota & Weerasinghe, 2005). Improved varieties Bw 267-3 and Bw 367 also demonstrated high tolerance at multiple growth stages (Wijerathna *et al.,* 2013; Dilhani *et al.,* 2026). Advanced breeding lines such as *Bg 300, Madathawalu*, and *BW 14-820* exhibited extreme tolerance across vegetative and reproductive stages (Siriwardana *et al.,* 2019).

Low fertilizer adaptability

Traditional varieties often thrive under low-input conditions due to efficient nutrient uptake and seedling vigor. Mayamulla *et al.* (2017) demonstrated that seed nutrient content (N, P, K) and seed weight of 40 improved varieties correlated positively with seedling vigor and subsequent yield under low fertility soils. These traits are important for organic and low-input cultivation, highlighting the potential of traditional and locally adapted varieties for sustainable rice production systems.

Nutritional and health benefits of traditional rice varieties

Traditional Sri Lankan rice varieties are valued not only for their agronomic significance but also for their nutritional composition and potential health benefits. These varieties often differ from modern improved rice types in their nutrient profiles, bioactive compounds, and biological effects on human health.

Nutrient composition of traditional rice

Traditional rice varieties contain a range of macro- and micronutrients important for human health, including proteins, dietary fiber, vitamins, minerals, and trace elements. A comparative analysis of several Sri Lankan traditional rice varieties showed variable but nutritionally beneficial trace element content, with essential elements such as selenium (Se), copper (Cu), and phosphorus (P) present across different cultivars while toxic elements (e.g., cadmium and arsenic) remained low and below recommended food safety limits (*Kalu Heenati, Rathu Heenati, Pragathi Wee, Weda Heenati*) an aspect important for consumer safety and nutrition (Rebeira *et al.,* 2022; Jayadewa *et al.,* 2023). Studies evaluating multiple rice varieties found that protein content across traditional and improved rice types varied, with some traditional cultivars exhibiting intermediate amylose profiles and comparatively richer dietary fiber and total ash (mineral content) levels, although differences in crude protein content were sometimes more pronounced in specific improved lines (At 373, H4) depending on variety and conditions (Rebeira *et al.,* 2022). Traditional Sri Lankan rice such as *Suwandel, Sudu Heenati*, and *Rath Suwandal* has been reported to contain 10-13% protein and notable amounts of dietary fiber, alongside carbohydrate levels that contribute slowly to blood glucose due to their lower glycemic index (GI). For example, *Pachchaperumal* may have a GI below 40 and *Kalu Heenati* below 55, which is favorable for diabetes management and glycemic control (Arachchilage & Ekanayake, 2024). Mineral composition studies also show that red pericarp varieties tend to be richer in minerals such as potassium (K), magnesium (Mg), calcium (Ca), and phosphorus compared with white pericarp varieties, making them good contributors to daily mineral intake (Kulasinghe *et al.,* 2018).

Bioactive compounds: antioxidants, anthocyanins, γ-oryzanol

A defining nutritional advantage of many traditional rice varieties lies in their bioactive compound content especially the phenolic acids, proanthocyanidins, anthocyanins, and γ-oryzanol concentrated in bran and pigmented pericarps. These compounds are potent antioxidants that help neutralize free radicals associated with oxidative stress and chronic disease risk. Pigmented varieties such as *Sudu Heenati*, *Beheth Heenati*, *Madathawalu*, *Rath Kadha*, and *Pachchaperumal* exhibit higher total phenolic content, proanthocyanidins, and other phytochemicals compared with white rice. These include hydroxycinnamic acids such as ferulic and p-coumaric acids, as well as tocopherols and tocotrienols (vitamin E homologues), which contribute to antioxidant activity (Jayadewa *et al.,* 2023). Traditional red varieties also had higher protein, fiber, and vitamin E content alongside balanced amino acid profiles than the improved varieties tested, indicating broader nutritional

advantages beyond antioxidants alone (Gunaratne *et al.,* 2013; Kulasinghe *et al.,* 2018).

Pigmented rice's anthocyanins and proanthocyanidins are especially important: anthocyanins are water-soluble pigments responsible for red, purple, or black pericarp colors and are linked to antioxidant, anti-inflammatory, and cardioprotective effects in various plant foods (Callcott *et al.,* 2020; Chen *et al.,* 2023). Although specific anthocyanin data for many Sri Lankan varieties remain emerging, research in pigmented rice landraces more broadly shows that black-bran rice can contain significant anthocyanin levels, which contribute to higher total antioxidant activity (e.g., up to ~39.7 mg cyanidin-3-glucoside per 100 g in Indian pigmented rice) relative to non-pigmented rice (Gogoi *et al.,* 2025).

Health benefits and functional effects

The nutrient and bioactive profiles of traditional rice varieties suggest multiple health benefits:

Glycemic control

Low GI in varieties like *Pachchaperumal* and *Rath Suwandal* supports slower glucose release, beneficial for metabolic health and diabetes management (Arachchilage & Ekanayake, 2024).

Antioxidant protection

Higher levels of phenolics, proanthocyanidins, γ-oryzanol, and vitamin E in pigmented rice are associated with enhanced free radical scavenging, which may contribute to reduced oxidative stress and lower risk of chronic diseases such as cardiovascular disease and cancer (Jayadewa *et al.,* 2023).

Micronutrient support

Rich mineral content, including selenium and essential trace elements, supports immune function, metabolic processes, and micronutrient adequacy in populations where deficiencies are common (Kulasinghe *et al.,* 2018).

Digestive health

Higher dietary fiber content in less polished traditional rice may improve gut health and bowel function, and possibly inhibit post-meal glucose spikes (Rebeira *et al.,* 2022).

However, while many biochemical studies show in vitro antioxidant properties, direct causative health effects in human populations require more clinical research. Nutrient bioavailability how well the body absorbs and uses these nutrients depends on preparation methods, degree of milling, and dietary context

Comparative analyses indicate that nutrient composition varies considerably between traditional and improved rice varieties. Improved varieties may have higher crude protein, but traditional varieties especially pigmented and less processed forms often contain greater dietary fiber, essential minerals, and bioactive antioxidants (Gunaratne *et al.,* 2013; Rebeira *et al.,* 2022).

While not all traditional rice consistently outperforms modern varieties in every nutrient category, nutritional advantages of traditional varieties emerge in specific components such as mineral density, antioxidant potential, phenolic composition, and favorable glycemic responses. These differences underscore the value of conserving and promoting traditional varieties as part of diversified, nutrient-rich diets.

Genetic and breeding potential of traditional rice in Sri Lanka

Traditional rice accessions in Sri Lanka represent a rich reservoir of useful genes that are increasingly recognized for their value in modern breeding programs. Molecular studies using Simple Sequence Repeat (SSR) markers have revealed high levels of genetic variation and unique allelic profiles among traditional varieties, indicating considerable untapped genetic diversity that can be harnessed for future improvement strategies. These varieties also exhibit wide variation in key morphological and physiological traits, such as plant architecture, root characteristics, and phenology, reflecting long-term adaptation to diverse microclimates, low-input conditions, and local stress environments (Jeewani *et al.,* 2023). Such diversity is not only evident in traditional traits but also in agronomic quality parameters, including grain size, cooking quality, and micronutrient content, which modern varieties often lack (Sinthuja *et al.,* 2021). Furthermore, studies assessing drought and salinity tolerance among Sri Lankan traditional rice varieties have identified specific accessions with superior performance under water-limited and high-salinity conditions, indicating that traditional germplasm harbors alleles valuable for developing stress-resilient cultivars (Munasinghe *et al.,* 2017; Beena *et al.,* 2021). This genetic richness underscores the critical role of traditional rice in broadening the genetic base of cultivated rice and in addressing future challenges related to climate change, nutritional security, and sustainable productivity.

Stress tolerance and adaptation traits

Sri Lankan traditional rice landraces possess valuable adaptive traits that confer enhanced tolerance to a range of abiotic stresses, making them important genetic resources for developing climate-resilient cultivars. Several studies have identified traditional accessions with superior drought tolerance, which is associated with physiological adaptations such as high leaf chlorophyll content, efficient water use, and robust root systems under water limitation (Sandhu *et al.,* 2019). In addition to drought, traditional varieties have shown promising responses to salinity and temperature stress, indicating the presence of useful alleles for broad stress adaptation (Zeng & Shannon, 2000). For example, genetic analyses of diverse rice landraces have revealed quantitative trait loci (QTLs) linked with tolerance

to multiple stresses, including heat, submergence, and oxidative stress, suggesting that these complex traits can be introgressed into elite backgrounds through informed breeding strategies (Kumar *et al.,* 2014). Moreover, traditional germplasm often exhibits slower senescence and maintenance of photosynthetic activity under stress conditions compared with modern high-yielding cultivars, supporting their potential use in breeding programs targeting sustainability under climate variability (Muthurajan *et al.,* 2015). The stress-adaptive characteristics of Sri Lankan traditional rice accessions underscore their importance as donors of alleles that can enhance resilience, yield stability, and environmental adaptability in future rice improvement efforts.

Grain quality characteristics and nutritional status

Traditional Sri Lankan rice varieties exhibit considerable variation in grain quality and nutritional traits, including differences in kernel size, shape, amylose content, gelatinization temperature, and cooking characteristics, which are important for both consumer preferences and nutritional value. Studies comparing traditional and modern rice genotypes have documented significant variation in grain physical properties, proximate composition, and functional quality traits, suggesting that traditional accessions may carry alleles that contribute desirable eating and cooking qualities not found in elite cultivars. In addition to physical attributes, variation in micronutrient concentrations such as iron, zinc, and essential amino acids has been observed among traditional landraces, indicating their potential as genetic donors for breeding nutritionally enhanced rice varieties. These quality and nutritional attributes also influence consumer acceptance and market value, making them valuable targets for breeding programs that aim to combine superior grain quality with stress tolerance and yield stability (Juliano, 2010). Overall, the rich diversity of grain quality phenotypes in Sri Lankan traditional rice germplasm provides an important genetic resource for developing more nutritious and market-preferred rice cultivars.

Implications for breeding and future improvement

The wide genetic diversity present in Sri Lankan traditional rice landraces highlights their critical role as parental material for pre-breeding and varietal development programs. These germplasm collections harbour alleles for stress tolerance, nutrient efficiency, and grain quality traits that are often absent in modern elite cultivars, making them valuable donors for introducing novel traits into breeding pipelines (Gamuyao *et al.,* 2012). Long-term adaptation of these varieties to diverse local environments has shaped unique combinations of morphological, physiological, and biochemical traits, providing opportunities to enhance resilience to drought, salinity, and temperature extremes (Vikram *et al.,* 2011). There is a growing global and national shift toward organic and sustainable agricultural practices driven by increasing concerns over environmental health, food safety, and the rising cost and negative impacts of synthetic agrochemicals. In Sri Lanka, this transition has encouraged the use of organic nutrient sources such as plant extracts, organic waste-derived fertilizers, and fish waste–based formulations, which have demonstrated positive effects on crop growth and yield (Pushpakumari & Suthajini, 2023; Wijesundara *et al.,* 2025, 2026). Traditional rice varieties are particularly well suited for organic farming systems due to their inherent adaptability to low-input conditions, resilience to environmental stress, and stable performance under natural nutrient management (Kasthurirathna *et al.,* 2025). Therefore, integrating organic inputs with the cultivation of Sri Lankan traditional rice aligns well with current trends toward environmentally sustainable and resource-efficient agricultural production systems. Incorporating traditional germplasm into breeding programs can thus support the development of climate-resilient, nutritionally enriched, and high-quality rice varieties while maintaining genetic diversity in cultivated populations. Such approaches are crucial for sustainable rice production in Sri Lanka and for global efforts to mitigate the impacts of climate change on food security.

Genetic diversity, molecular evidence, and conservation

Complementary investigations focusing on ex-situ conserved cultivars such as *Kaluheenati* have further confirmed these patterns. Molecular characterization using 30 SSR markers revealed 147 alleles and multiple distinct genetic clusters among the accessions, reinforcing evidence of high polymorphism and diverse genetic backgrounds even within a single cultivar population (Jeewani *et al.,* 2023). Cluster and phylogenetic analyses also demonstrated that accessions do not always cluster strictly by name or origin, emphasizing the rich allelic variation that can be harnessed for trait improvement and selection of parental lines in future breeding strategies.

In addition, studies on other traditional rice cultivars conserved in Sri Lankan gene banks, such as "*Hondarawala*", have shown significant genetic variation at the molecular level. Alongside morphological diversity, SSR marker analysis identified over 120 alleles across tested accessions with polymorphic information content values indicating moderate to high variability, illustrating the value of molecular assessment in capturing the breadth of diversity present across traditional germplasm (Kekulandara *et al.,* 2022).

Molecular studies on the traditional cultivar *Suwandel* demonstrate multiple distinct clusters with no duplicates detected among conserved accessions, further illustrating that even closely related germplasm maintain distinct genetic identities and should be conserved as unique genetic resources (Gunasena *et al.,* 2016).

National gene bank collections in Sri Lanka preserve hundreds of unique traditional rice cultivars ex situ, which are essential for long-term breeding use and future crop improvement. Molecular analyses of a broader panel of 100 traditional rice varieties using 33 SSR loci detected 387 alleles with high polymorphism levels and genetic structuring into well-separated clusters, demonstrating

the broad genetic variation conserved within ex situ collections and its value for utilisation in both breeding and conservation strategies (Weerakoon & Somaratne, 2021). Furthermore, studies on other locally important varieties, such as *Pachchaperumal*, have also identified substantial SSR-derived allelic variation among conserved accessions, reinforcing the breadth of molecular diversity available within Sri Lanka's traditional rice gene pool (Jeewani *et al.,* 2023).

Together, these molecular marker studies confirm that Sri Lankan traditional rice germplasm harbours significant genetic diversity and structured variation, making it invaluable for in situ and ex situ conservation as well as for selecting genetically diverse parental lines in future rice breeding programs that aim to enhance stress adaptation and nutritional traits.

Maintaining both ex situ gene bank collections and sustained on-farm cultivation by farmers is essential for preserving genetic variety, especially given the rapid replacement of traditional cultivars with contemporary high-yielding varieties and the continual risk of genetic erosion (Dwivedi *et al.,* 2017). Ex situ conservation, such as that carried out by the Plant Genetic Resources Centre (PGRC) in Sri Lanka, safeguards a broad spectrum of genetic variants by storing seeds under controlled conditions, which helps prevent loss of rare alleles and ensures availability for future breeding and research (FAO, 2010). At the same time, in situ cultivation through farmer participation maintains adaptive evolutionary processes, allowing traditional rice genotypes to continue evolving in response to local environmental stresses, biotic pressures, and cultural preferences (Brush, 2000). This dynamic on-farm conservation preserves not only allelic diversity but also ecologically and culturally valuable traits that may not be captured in seed banks alone (Ramírez-Restrepo *et al.,* 2019). The long-term preservation and sustainable use of Sri Lanka's indigenous rice genotypes therefore depend on these conservation strategies working together, integrating ex situ safeguarding with in situ evolutionary adaptation to maximize genetic diversity and resilience in future breeding programs.

Application of traditional germplasm in modern breeding

The integration of traditional rice germplasm into modern breeding programs through quantitative trait locus (QTL) introgression and marker-assisted breeding (MAB) has greatly expanded the potential for improving complex adaptive traits in elite cultivars. Traditional landraces frequently harbour valuable abiotic stress tolerance QTLs that are absent or rare in high-yielding breeding lines, making them an essential source of genetic variation for crop improvement (Marè *et al.,* 2023). By identifying robust molecular markers linked to these QTLs, breeders can accurately transfer desirable traits into elite genetic backgrounds while minimizing linkage drag. A prominent example of this is the *Saltol* QTL, which confers seedling stage salinity tolerance and has been successfully introgressed into several high yielding rice cultivars, including the widely cultivated Pusa Basmati, through marker-assisted backcross breeding, resulting in near-isogenic lines (NILs) with enhanced tolerance and agronomic performance comparable to the recurrent parent (Yadav *et al.,* 2020).

The utility of *Saltol* extends beyond Basmati rice; it has also been deployed in non-Basmati backgrounds such as Pusa44 and Sarjoo52, where NILs developed through marker-assisted backcrossing exhibited significantly improved salinity tolerance metrics such as Na^+/K^+ homeostasis and low salt injury scores, demonstrating the broad applicability of traditional germplasm in different genetic contexts (Krishnamurthy *et al.,* 2020). Recent breeding efforts have even used advanced SNP-based genotyping in Japonica backgrounds to introgress *Saltol* into temperate rice varieties, illustrating how traditional QTLs can be mobilized across diverse rice subspecies using modern molecular breeding tools (Marè *et al.,* 2023). These successes highlight how traditional rice germplasm continues to provide essential allelic resources that can be harnessed through marker-assisted approaches to improve stress adaptation, accelerate trait incorporation, and expand the genetic base of modern rice varieties.

Alleles important for nutrient shortage tolerance and other stress responses are also present in traditional rice germplasm, making landraces valuable donors for breeding programs that target complex abiotic stresses. For instance, phosphorus deficiency tolerance QTLs such as *Pup1* originally discovered in traditional donors like *Kasalath* have been widely validated using Pup1-linked molecular markers and shown to improve phosphorus uptake and yield under P-deficient conditions, demonstrating their utility for marker-assisted selection (Nirubana *et al.,* 2020). In particular, Pup1 shows significant haplotypic variation among diverse rice accessions, illustrating genetic diversity for nutrient stress tolerance that can be incorporated into modern cultivars.

In addition to individual QTL introgressions, gene pyramiding strategies that combine multiple stress-related loci from traditional and donor backgrounds are increasingly used to develop varieties with enhanced resilience to multiple abiotic stresses. For example, pyramiding major QTLs for drought tolerance (*qDTY1.1*), salinity tolerance (*Saltol*), and other stress responses has been effective in producing improved rice lines that maintain yield under drought and salinity conditions (Roy *et al.,* 2022; Renuprasath *et al.*, 2023). Similarly, mapping and validation of salinity tolerance QTLs from traditional landraces like *Pokkali* and *Horkuch* have identified multiple genomic regions associated with salt adaptation, which can be exploited to develop tolerant cultivars through marker-assisted breeding (De Leon *et al.,* 2017; Haque *et al.,* 2022).

The value of multi-locus introgression is also evident in breeding efforts that integrate stress tolerance loci such as *Pup1* (phosphorus deficiency) along with submergence tolerance (*Sub1*) into elite backgrounds, demonstrating both the potential and complexity of combining QTL effects

for multiple stresses. These breeding initiatives illustrate that pre-breeding and introgression techniques employing traditional germplasm not only allow resilience traits to be combined with high yield potential but also provide a genetic basis for the development of climate-adaptive rice cultivars suited to the diverse environmental challenges faced in contemporary intensive rice production systems.

Future breeding strategies for climate-resilient and nutritious rice

High-throughput phenotyping (HTP) and advances in genomics are revolutionizing rice breeding by making it possible to combine genomic selection with conventional breeding techniques to hasten the creation of climate-resilient and nutritionally improved cultivars. Genomic selection (GS), which uses genome-wide marker information to estimate genomic estimated breeding values (GEBVs), enables breeders to capture complex polygenic traits such as drought tolerance, salinity resistance, and submergence tolerance more efficiently than traditional marker-assisted selection because it accounts for small-effect loci distributed across the genome. Integrating genomic selection with multi-environment phenotyping and environmental covariates has been shown to significantly improve predictive ability for key adaptive traits such as plant height, flowering time, and grain yield across diverse target environments

Coupling GS with high-throughput phenotyping technologies such as field-based imaging, sensor networks, and automated trait extraction allows breeders to monitor complex traits like root architecture, stomatal conductance, biomass, and canopy temperature at scale, which can substantially enhance the precision of selection and shorten breeding cycles (Sinha *et al.,* 2023). Machine learning and artificial intelligence (AI) tools are increasingly incorporated into breeding pipelines to analyse HTP and genomic data, enabling better prediction of phenotypes and genotype-by-environment interactions, which accelerates genetic gains for stress resilience and productivity.

In addition to GS and HTP, innovative breeding informational infrastructures such as *Connected Breeding* and "Trait-to-Environment" strategies are being deployed to harness genomic variation from gene banks and integrate it into elite lines under real stress environments, thereby improving resilience under drought, salinity, and flooding. These holistic approaches combining genomic selection, high-throughput phenotyping, big data analytics, and environment-focused breeding frameworks are expected to accelerate the development of climate-smart, nutritious rice varieties that can meet future food security challenges while maintaining adaptation to diverse agroecological conditions.

In order to ensure local adaptation and adoption of novel rice varieties, it is increasingly acknowledged that participatory breeding approaches which actively involve farmers in selection and evaluation are essential to bridge the gap between scientific breeding objectives and real-world farming needs. Farmer participation assists in identifying agronomic, cultural, and market-relevant traits that conventional breeding programmes may overlook, such as grain quality, taste, lodging resistance, and pest tolerance, which are important for farmer adoption in specific agro-ecological settings (FAO, 2020). Participatory varietal selection (PVS) studies demonstrate that when rice lines are evaluated in farmers' fields under realistic management conditions, farmers frequently prioritise a broader range of traits than breeders alone, resulting in the selection of lines that perform well agronomically and match local preferences, thereby improving adoption potential (Aristya *et al.,* 2021).

In rainfed and marginal environments such as those in Indonesia, integrated participatory breeding programmes involving hundreds of farmers have successfully identified genotypes that combine yield stability, environmental resilience, and preferred traits, highlighting the value of farmer-driven evaluation for sustainable agriculture under climate stress (Aristya *et al.,* 2025). Meta-analyses further show that on-farm participatory approaches increase the diversity of farmers' preferred varieties and enhance the rate of adoption because farmers are more likely to cultivate and disseminate varieties they helped select, especially when trait evaluation reflects local biotic and abiotic conditions. In addition, participatory varietal selection in coastal and flood-affected areas of South and Southeast Asia revealed that farmers often select varieties with traits such as salt tolerance, plant stature, and maturity timing that differ from breeder-centric criteria, leading to improved yield stability and higher adoption rates in smallholder communities (Burman *et al.,* 2018).

These examples demonstrate that participatory breeding and varietal selection empower farmers, better address location-specific needs, and contribute to the development and dissemination of climate-resilient and locally accepted rice varieties. By combining scientific performance data with farmers' context-based priorities, participatory approaches can accelerate varietal adoption and enhance resilience under changing climatic conditions.

Nutritional improvement in modern rice breeding

In addition to enhancing stress resistance, contemporary rice breeding is increasingly concentrating on improving nutritional quality to address hidden hunger and micronutrient deficiencies in rice-dependent populations. The aim of biofortification approaches is to develop high-yielding, climate-resilient cultivars that simultaneously exhibit increased levels of essential micronutrients such as iron (Fe), zinc (Zn), and provitamin A (β–carotene) in the grain, thereby contributing to both food and nutritional security (Bouis & Saltzman, 2017). Many traditional rice landraces naturally accumulate higher concentrations of micronutrients and antioxidant compounds than modern varieties, making traditional germplasm an important source of alleles for nutrient density traits (Swamy *et al.,* 2016). For example, donors such as *Chakhao*, *Kala Namak*, and several aromatic landraces have been identified with significantly

elevated grain zinc and iron content, and these have been deployed in marker-assisted backcrossing programs to enhance the micronutrient profile of elite breeding lines without compromising yield.

Integration of advanced breeding techniques including genomic selection, marker-assisted breeding, and information from participatory varietal selection enhances the ability to target complex traits such as micronutrient accumulation alongside agronomic performance, stress resilience, and grain quality. Such integrated approaches enable breeders to more efficiently capture favourable alleles from traditional germplasm while aligning varietal development with farmer and consumer preferences, ultimately producing productive and nutritionally enhanced climate-smart rice varieties that can help mitigate micronutrient deficiencies in Sri Lanka and other rice-growing regions.

Integrated approaches for sustainable rice development

A pathway toward sustainable rice development is represented by integrated approaches that combine genomics, high-throughput phenomics, participatory breeding, and nutritional trait enhancement. By leveraging traditional rice germplasm, breeding programs can directly utilize the extensive genetic diversity preserved in landraces, maintaining nutritional quality and adaptive traits while addressing challenges posed by climate change, abiotic stresses, and evolving food demands (Swamy *et al.,* 2016; Ceccarelli & Grando, 2022). These integrative strategies enable the simultaneous improvement of yield, resilience, and micronutrient content, while participatory and on-farm evaluation ensures that the resulting varieties are locally adapted and socially acceptable (Bouis & Saltzman, 2017; Burman *et al.,* 2018). Recent studies demonstrate that combining traditional germplasm with genomic selection, marker-assisted breeding, and phenomics-based trait monitoring accelerates the development of climate-smart, nutritionally enriched rice varieties, thereby promoting sustainable and resilient rice production systems in South and Southeast Asia (Muthu *et al.,* 2020; Sinha *et al.,* 2023).

Key challenges in traditional rice germplasm research in Sri Lanka

High-yielding improved rice varieties developed during the Green Revolution have progressively replaced many traditional rice landraces in Sri Lanka, leading to a substantial reduction in on-farm genetic diversity (FAO, 2010). Indigenous cultivars were historically valued for their broad genetic variability and strong adaptation to diverse local soils, climatic conditions, and low-input farming environments shaped through long-term farmer selection (Harlan, 1992; Suriyagoda *et al.,* 2011). In contrast, modern rice varieties were primarily bred for short growth duration, high responsiveness to fertilizer application, and enhanced productivity under irrigated cultivation systems, which accelerated their widespread adoption across major rice-growing regions (Khush, 2005). Consequently, the cultivation area of many native rice types has been severely restricted, and numerous traditional varieties that were once widely grown are now conserved mainly in ex situ gene banks, such as the Plant Genetic Resources Centre (PGRC), or maintained within small-scale traditional farming communities (Wickramasinghe *et al.,* 2022; Samaranayake *et al.,* 2017). This transition clearly illustrates an ongoing process of genetic erosion that threatens the conservation of locally adapted germplasm and limits the availability of valuable traits for future rice improvement and climate-resilient breeding efforts.

Morphological and physiological studies of Sri Lankan traditional rice varieties indicate substantial differences from modern improved cultivars in plant architecture, stress tolerance, and other adaptive traits (Munasinghe *et al.,* 2017). Contemporary breeding programs often prioritize yield, which can unintentionally reduce the frequency of important traits present in traditional landraces, including resistance to salinity, drought, and submergence (Khush, 2005). For instance, when Sri Lankan landraces were evaluated under water-limited conditions, several accessions demonstrated superior drought tolerance compared with commonly grown improved varieties (Munasinghe *et al.,* 2017). Beyond stress adaptation, traditional rice varieties also possess enhanced nutritional qualities, such as higher micronutrient content and favorable grain composition, which are frequently absent in modern high-yielding lines. These findings highlight the urgent need to actively conserve and integrate traditional germplasm into breeding programs to preserve these valuable adaptive and nutritional traits for future rice improvement and climate-resilient agriculture.

Sri Lankan traditional rice germplasm exhibits considerable genetic variation, as evidenced by molecular and agromorphological characterization (Suriyagoda *et al.,* 2011). However, this diversity is increasingly at risk because many landraces are no longer actively cultivated by farmers. Studies using SSR markers have shown that traditional accessions possess a wide range of allelic variation, reflecting a substantial pool of genetic diversity that remains underutilized in contemporary breeding programs. Despite this potential, the on-farm expression of these landraces is declining due to the dominance of modern high-yielding varieties, which has resulted in reduced cultivation of indigenous types (FAO, 2010). This reduction in farmer-maintained diversity not only limits the availability of unique adaptive traits but also increases the vulnerability of rice crops to biotic and abiotic stresses, underscoring the need for integrated conservation strategies that combine *in situ* and *ex situ* approaches.

Limited research, characterization, and utilization

Although Sri Lanka possesses a rich repository of traditional rice germplasm, comprehensive genomic and phenotypic evaluations remain limited. Only a small fraction of the available accessions has been systematically characterized, despite evidence from molecular marker studies, such as SSR analyses, showing that traditional landraces contain substantial genetic diversity.

Morphological and molecular assessments conducted on specific landrace collections, including *Kaluheenati*, have revealed significant variation in plant architecture, stress adaptation, and grain quality; however, comparable evaluations are lacking for the broader germplasm maintained at the Plant Genetic Resources Centre (Jeewani *et al.,* 2023). This insufficient characterization constrains the identification and utilization of valuable alleles that could enhance rice breeding programs, particularly for improving stress resilience, nutritional quality, and climate adaptation (Khush, 2005)

Weak integration of nutritional and stress-tolerance traits into breeding

Many Sri Lankan traditional rice landraces possess valuable adaptive traits, including drought resilience, deep root systems, and tolerance to salinity and anaerobic stresses, which are beneficial for stress adaptation in rainfed and marginal environments (Munasinghe *et al.,* 2017). Phenotypic and molecular studies have identified several traditional accessions with superior drought tolerance and distinctive root phenotypes, suggesting that deep root traits could be exploited in breeding for water-limited conditions (Munasinghe & Price, 2016). Despite the availability of such genetic resources, formal breeding programs in Sri Lanka have made limited progress in systematically integrating these adaptive traits into high-yielding cultivars, partly due to the complex genetic architecture of stress tolerance and the multigenic nature of many tolerance traits (Sandeep & Godi, 2023). Furthermore, the challenge of combining enhanced nutritional quality with stress tolerance in conventional rice breeding is compounded by limited phenotypic screening protocols and a lack of comprehensive trait-linked genomic markers, resulting in missed opportunities for developing cultivars with both high yield and resilience to biotic and abiotic stresses (Beena *et al.,* 2021). This weak integration ultimately slows progress toward climate-resilient and nutritionally superior rice varieties that could support food security in variable environments.

Environmental sensitivity and photoperiod response limiting wider adoption

The varied photoperiod responses and environmental sensitivities of Sri Lankan traditional rice accessions restrict their wider adoption and consistent performance across diverse agro-ecological zones. Research conducted on a core collection of traditional rice germplasm has shown that temperature and day length significantly influence vegetative growth traits such as days to fully expanded leaves and plant height, with different accessions responding differently under short-day, day-neutral, and long-day conditions (Rathnathunga & Geekiyanage, 2017; Rathnathunga *et al.,* 2019). Studies on very early maturing Sri Lankan traditional rice accessions further confirm significant differences in days to flowering under contrasting photoperiods, indicating that many traditional types are highly sensitive to day length (Padukkage *et al.,* 2017; Pushpakumari *et al.,* 2025b). The influence of photoperiod on flowering time and yield components has also been documented in broader rice research, where photoperiod genes such as *Hd1*, *Ghd7*, and *DTH8* interact to determine rice adaptation to specific day lengths (Subudhi *et al.,* 2018). Such differential responses mean that many traditional landraces are suited only to particular seasonal environments and may not flower or reach maturity under non-inductive photoperiods, limiting their practical cultivation throughout the year without careful seasonal management. This sensitivity reduces the stability of performance across locations and complicates efforts to breed for broad adaptation, as selecting for wide environmental stability requires overcoming complex interactions between genetic photoperiod sensitivity and local growth conditions (Rathnathunga *et al.,* 2019; Pushpakumari *et al.,* 2025b).

Socio-economic, policy, and conservation constraints

The production, conservation, and sustainable use of Sri Lanka's traditional rice germplasm are constrained by significant socioeconomic and policy issues that discourage farmers from maintaining these varieties. Traditional rice cultivars typically have lower grain yields and longer maturity periods compared with modern improved varieties, making them less competitive under market-driven production systems where short duration and high yield are prioritized (FAO, 2010). As a result, farmers tend to prefer high-yielding cultivars that are more economically attractive, reducing the total area under traditional rice cultivation and diminishing the incentives for on-farm conservation of diverse landraces. Limited commercial cultivation and poor market availability of traditional rice further exacerbate this reduction in farmer adoption; without strong policy frameworks that recognize and reward farmers' traditional knowledge and provide incentives for conservation, these varieties remain niche commodities only in small specialty markets (Department of Agriculture/ HARTI, 2025).

In addition, the absence of comprehensive marketing infrastructure, value-adding systems, and official support mechanisms discourages investment in traditional rice cultivation and undermines the capacity of rural communities to benefit financially from biodiversity conservation (Dhanapala, 1999; Department of Agriculture/ HARTI, 2025). These socioeconomic constraints, coupled with weak legislative protection and limited public awareness, impede efforts to promote sustainable use and long-term conservation of Sri Lanka's traditional rice genetic resources.

Furthermore, both in situ and ex situ conservation initiatives for Sri Lankan rice germplasm are constrained by limited institutional support and inadequate legal frameworks that recognize and protect plant genetic resources. Although large collections of traditional rice accessions are maintained at national conservation centers such as the Plant Genetic Resources Centre (PGRC) and other gene banks, infrastructure deficits, insufficient funding, and limited human capacity hinder effective long-term conservation and utilization (Wickramasinghe

et al., 2022). Coverage gaps in germplasm collections, especially for rare landraces and wild rice relatives, increase the risk of missing valuable alleles that are critical for future breeding efforts and climate resilience (Nayar & Sharma, 2018).

In addition, the decline of traditional rice cultivation in Sri Lanka is influenced by broader socioeconomic constraints, including limited formal market linkages for heritage varieties, inadequate institutional knowledge transfer, and low public awareness of the cultural, nutritional, and health significance of traditional rice. Without strategic policies that promote farmer participation in conservation, facilitate value–added markets, and provide targeted extension and training programs, traditional germplasm resources remain vulnerable to accelerated genetic erosion and the loss of distinctive agronomic and sensory traits (FAO, 2010; Sinthuja *et al.,* 2021). Strengthening legal safeguards, institutional capacity, and community-driven conservation initiatives is therefore essential to ensure the sustainable management and utilization of Sri Lanka's rice genetic heritage.

Conclusion

Sri Lankan traditional rice varieties represent a rich and underutilized reservoir of genetic diversity with significant potential for sustainable rice improvement. The review highlights significant variability across morphological, agronomic, adaptive, and nutritional traits, demonstrating the unique value of these varieties in addressing current and future agricultural challenges. Wide variation in vegetative characteristics such as plant height, effective tillers, leaf number and days to flowering. Similarly, the diversity observed in yield components, including number of grains per panicle, filled grain percentage, total panicle weight and hundred grain weight reflects differences in both yield potential and yield stability among traditional varieties.

Importantly, traditional varieties (*Suwandel*, *Kirimurunga*, *Kahatawee*, *Devareddiri*, *Sulai*) exhibit inherent tolerance to environmental stresses such as drought, submergence, and poor soil fertility, making them highly suitable for climate-resilient agriculture.

In addition to agronomic advantages, the superior nutritional quality of pigmented and specialty rice types, characterized by high antioxidant content, micronutrients, and dietary fiber, further enhances their importance in promoting food and nutritional security. Despite these advantages, the cultivation area of traditional rice has declined due to the widespread adoption of high-yielding modern varieties. Therefore, systematic conservation, characterization, and utilization of traditional germplasm are essential. Integrating these valuable genetic resources into modern breeding programs, promoting value addition and n markets, and strengthening farmer awareness can support their sustainable utilization.

Author contributions

W. D. D. N. Chandrarathne and P. V. D. N. N. T. Kumarasena contributed to the conceptualization, methodology development, and preparation of the original draft. B. S. M. A. K. Senevirathne contributed to the review and editing of the manuscript. A. G. H. Prabhashwaree assisted with manuscript review and editing. A. A. B. S. Amarasinghe contributed to supervision and provided critical review and editing of the manuscript. All authors have read and approved the final version of the manuscript.

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