REVIEW ARTICLE

Phenotypic and molecular diversity of Nepalese rice (*Oryza sativa* l.) landraces: a comprehensive review of characterization, evaluation, and conservation strategies

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Abstract

Nepal is in a unique place between the Indo-Gangetic plains and the foothills of the Himalayas.This location has made it home to roughly 2,500 traditional rice varieties that farmers have grown and selected over thousands of years. These landraces have a lot of genetic features that could help feed the planet as the climate changes. This review paper brings together what we know about these rice varieties from studies done between 2010 and 2025. The research shows wide differences in how these plants look and grow. Plant height ranges from 85 to 165 cm, flowering time spans 65 to 180 days, and grain weight varies from 15 to 35 grams per thousand seeds. When scientists looked at the DNA using SSR and SNP markers, they found high genetic diversity with expected heterozygosity between 0.42 and 0.78. Some landraces stand out for their useful traits. Varieties like Kalo Masino and Seto Bageri handle drought well, while Jumli Marsi grows at elevations above 2,800 meters where most rice would fail. Kalo Nuniya packs more iron and zinc than typical rice. However, these valuable landraces face serious threats. Modern high-yielding varieties have replaced many traditional ones, and about 33% of landrace diversity has vanished in recent decades. We need better conservation efforts, more thorough studies using modern tools, and smart breeding programs that tap into this genetic wealth. Without action, we risk losing these irreplaceable resources that took generations to develop.

Keywords: Rice landraces, genetic diversity, molecular markers, stress tolerance, Nepal

Introduction

Rice feeds more than half the world. Over 3.5 billion people count on it as their main food, and it provides about 20% of all the calories humans eat (Muthayya *et al.,* 2014). With the world population heading toward 9.7 billion by 2050, we need to grow 25-30% more rice as a food than we do now. Rice feeds more than half the world. Over 3.5 billion people count on it as their main food, and it provides about 20% of all the calories humans eat (Muthayya *et al.,* 2014).

With the world population heading toward 9.7 billion by 2050, we need to grow 25-30% more rice than we do now. At the same time, weather patterns are becoming harder to predict, droughts hit more often, and temperatures keep climbing (Ray *et al.,* 2013; Van Oort *et al.,* 2015). Old rice varieties that farmers have grown for centuries might hold the answers we need. These landraces carry genes for surviving tough conditions that modern breeding programs have often overlooked (Zhao *et al.,* 2018; Kumar *et al.,* 2021). Nepal offers something special for rice research. The country stretches from 60 meters above sea level in the southern Terai plains up to 4,300 meters in the mountains. Between these extremes, you find tropical lowlands, temperate hills, and cold mountain valleys, each with its own climate and growing conditions. Farmers in these different zones have selected rice varieties suited to their local needs for thousands of years. The result is about 2,500 distinct landraces, making Nepal one of the most important places in the world for rice genetic diversity (Joshi *et al.*, 2012; Upadhyay *et al.,* 2015). Some of these Nepalese varieties have become famous for their remarkable traits. Take Jumli Marsi, for example. This aromatic rice grows at elevations between 2,200 and 2,800 meters where winter temperatures would kill most rice plants. Farmers prize it for both its cold tolerance and its premium grain quality. Then there is Anadi, a sticky rice that people use for special dishes and ceremonies. Kalo Nuniya, a black rice variety, contains high levels of anthocyanins and minerals that make it nutritionally valuable (Rai *et al.,* 2023; Ghimire *et al.,* 2013). Many landraces also resist diseases like brown spot, blast, and sheath blight better than modern varieties do (Lamsal *et al.,* 2024; Rajan *et al.,* 2019). Despite their importance, these genetic resources face real danger. When high-yielding modern varieties arrived in Nepal during the Green Revolution, many farmers switched from their traditional seeds. This made economic sense at the time, but it meant that old varieties started disappearing from fields. Climate change adds another pressure, especially on mountain varieties that cannot simply move uphill as temperatures rise. Research on Nepalese landraces has been scattered across different institutions and focused on different aspects without much coordination (Neupane *et al.,* 2020; Poudel *et al.,* 2020; Gauchan *et al.,* 2012). This review pulls together what scientists have learned about Nepalese rice landraces. We look at how diverse they are in terms of physical traits and DNA markers. We examine which varieties tolerate drought, cold, and diseases. We assess the current state of conservation efforts and identify what still needs to be done. Our goal is to show why these landraces matter for the future of rice breeding and food security, and to point out the gaps in our knowledge that future research should address.

Origin and distribution of Nepalese rice landraces

Historical background

People have grown rice in Nepal for about 4,500 years. The Terai region in the south connects to the great Indo-Gangetic plain where indica rice was first domesticated (Meadow, 1996; Fuller, 2011). But Nepal is not just an extension of the Indian plains. The dramatic rise in elevation as you move north created very different growing conditions. Over time, rice adapted to these varied environments. Trade routes through the Himalayas also brought japonica rice from China and Tibet. When these two rice types met and mixed, they created new genetic combinations found nowhere else (Glaszmann, 1987; Garris *et al.,* 2005; Wang *et al.,* 2018). Nepalese farmers developed their own ways of classifying and selecting rice. They paid attention to grain shape, cooking quality, how long the rice took to mature, and how it performed in their particular fields. This knowledge passed from parent to child, and seeds moved between families and villages through traditional exchange networks. Each community maintained varieties suited to their specific needs, whether that meant early maturity to fit a short growing season, tolerance to flooding in low-lying areas, or resistance to local pest problems (Sthapit *et al.,* 1996; Rana *et al.,* 2000; Joshi *et al.,* 2001).

Distribution across agro-ecological zones

Nepal divides naturally into three main zones, and each has its own set of rice varieties. The Terai zone runs along the southern border at elevations below 300 meters. Here the climate is hot and humid, and farmers grow mainly indica-type rice. These lowland varieties tiller heavily, respond to the changing day length, and can handle the heat. Some mature quickly in 90 days while others take 180 days, giving farmers flexibility in their cropping schedules (Subedi *et al.,* 2024; Thapa *et al.,* 2022). The hill zone from 300 to 2,000 meters is home to rice that shows mixed ancestry between indica and japonica. These varieties have adapted to growing on terraced slopes with acidic soils and unpredictable rainfall (Shrestha *et al.*, 2024; Verma *et al.,* 2021). Finally, the mountain zone above 2,000 meters has mostly japonica-type rice. These cold-tolerant varieties can grow at elevations approaching 3,000 meters in sheltered valleys of districts like Jumla, Dolpo, and Mustang (Ghimire *et al.,* 2013).

Morphological and agronomic traits

Plant structure

Studies using standard rice descriptors from the International Rice Research Institute have documented wide variation in how Nepalese landraces look and grow. Subedi et al. (2024) measured 49 landraces and found plant heights ranging from 85 cm to 165 cm. About 71% of these varieties had bent culms that help them resist lodging in wind and rain. The number of productive tillers per plant varied from 8 to 25, with hill varieties generally producing more tillers than lowland ones (Thapa *et al.,* 2022). Leaf characteristics also differ substantially. Leaf blades range from 28 to 45 cm long and 1.2 to 2.8 cm wide. Flag leaf angle, which affects how much light reaches lower leaves, varies from nearly upright to quite droopy. Mountain landraces tend to have shorter, sturdier stems that stand up better to the harsh conditions at high elevation (Ghimire *et al.,* 2013).

Flowering and maturity

Time to flowering shows enormous range in Nepalese rice. Early Terai varieties can flower in just 65 days after planting, while late-maturing photoperiod-sensitive types take 180 days (Kharel *et al.,* 2022). This diversity lets farmers plant rice at different times and harvest across an extended season rather than all at once. Panicle length runs from 18 to 32 cm with anywhere from 120 to 350 spikelets per panicle. Spikelet fertility, meaning how many flowers actually set seed, ranges from 75% to 95%. Hill and mountain varieties typically show better fertility rates because they have adapted to shorter growing seasons (Neupane *et al.*, 2020., Adhikari *et al.*, 2019).

Grain features

Grain shape and size vary widely, reflecting both genetic diversity and what different communities prefer for cooking. Grain length spans from 4.2 mm to 8.6 mm, width from 1.8 mm to 3.4 mm, and thickness from 1.4 mm to 2.2 mm. This covers the full range from short round grains to long slender ones (Rai *et al.,* 2023). Thousand-grain weight ranges from 15 to 35 grams, with mountain varieties generally having heavier grains because cooler temperatures allow longer grain filling periods. Grain color is particularly interesting. While most commercial rice is white, Nepalese landraces come in brown, red, purple, and black. These colored varieties are mostly found and concentrated in the hill and mountain regions where they hold cultural significance and are increasingly valued for their health benefits (Poudel *et al.,* 2020; Chen *et al.,* 2024).

Stress tolerance

Drought tolerance

Finding rice that can handle water shortage matters more each year as rainfall becomes less reliable. Lamichhane *et al.,* (2025) tested twelve landraces from Far-West Nepal under controlled drought conditions. They used several mathematical indices to measure how well each variety coped with water stress, including the stress tolerance index, mean productivity, geometric mean productivity, and yield index. Three varieties stood out as particularly drought tolerant: Kalo Masino, Seto Bageri, and Rato Anadi. These had STI values above 1.0 and lost relatively little yield when water was scarce. Five other varieties including Temase, Chiudi, Batebudo, Sauthyari, and Ghiupuri also performed well, losing less than 15.9% of their yield under drought. What makes these varieties drought tolerant? Several factors seem to contribute. Their roots grow deeper, reaching more than 40 cm into the soil to find water. They also maintain a higher ratio of root to shoot biomass, sometimes exceeding 0.4. Under stress, they accumulate proline and other compounds that help cells retain water and function normally. Their leaves may be smaller or thicker, and their stomata close more quickly to reduce water loss (Pandey and Shukla, 2017). Recent work has also shown that drought-tolerant landraces form stronger partnerships with beneficial soil fungi called mycorrhizae, which helps plants access water and nutrients.

Cold tolerance

High-altitude rice from Nepal can survive conditions that would kill ordinary varieties. Jumli Marsi is the best-known example. It grows and sets seeds at elevations above 2,800 meters where nighttime temperatures during the growing season can drop to 5 degrees Celsius. Most rice suffers severe damage when exposed to temperatures 8 to 10 degrees below what Jumli Marsi can handle (Ghimire *et al.,* 2013). This cold tolerance comes from several adaptations. Cell membranes contain different fats that stay flexible at low temperatures. Antioxidant enzymes like superoxide dismutase, catalase, and peroxidase work harder to protect cells from cold damage. The plants also produce protective proteins and other molecules that prevent ice crystals from forming. Scientists have identified some of the genes responsible. Cold-tolerant Nepalese landraces carry working versions of genes called OsMYB3R-2, OsWRKY71, and OsCBF3. These genes control networks of other genes that respond to cold stress (Bhandari *et al.,* 2019). Understanding these genetic mechanisms could help breeders transfer cold tolerance to other rice varieties.

Disease resistance

Brown spot disease, caused by the fungus *Bipolaris oryzae*, creates serious problems in rainfed and upland rice areas. Lamsal *et al.,* (2024) tested 52 Nepalese landraces against this disease at the research station in Rampur, Chitwan. They used an alpha lattice design with three replications to ensure reliable results. The findings were sobering. Only nine landraces showed moderate resistance based on how much disease developed over time. Most varieties were susceptible or highly susceptible. Yield dropped significantly as disease severity increased, showing that brown spot directly hurts productivity. This means conservation and breeding programs need to pay more attention to incorporating disease resistance. For blast disease, the picture looks somewhat better. Hill and mountain landraces carry various resistance genes including Pi2, Pi9, Pita, and Pib. These provide protection against different races of the blast fungus (Shrestha *et al.,* 2013; Rajan *et al.,* 2021).

Grain quality and nutrition

Cooking quality

How rice cooks and tastes depend largely on its starch composition. Rai *et al.,* (2023) studied three popular Nepalese landraces in detail. Anadi, Bhotange, and Kalo Nuniya differ dramatically in their cooking properties. Amylose content, which determines whether cooked rice is sticky or fluffy, ranged from 8.2% in Anadi to 24.6% in other varieties. Gel consistency, indicating how soft the rice becomes, varied from 26 mm to 78 mm. Gelatinization temperature, which affects cooking time, fell between 68 and 74 degrees Celsius. Anadi with its low amylose and soft gel makes excellent sticky rice for desserts and special occasions. Several Nepalese varieties produce aromatic rice that commands premium prices. Jumli Marsi, certain Basmati types, and Kalo Masino all contain high levels of a compound called 2-acetyl-1-pyrroline, which creates the popcorn-like smell that people associate with fine rice. Laboratory analysis shows concentrations between 0.8 and 2.4 mg per kilogram, comparable to famous basmati varieties from India and Pakistan. The aroma comes from a non-functioning version of a gene called BADH2. When this gene does not work properly, the fragrant compound accumulates instead of being broken down (Sakthivel *et al.,* 2009; Bordoloi *et al.,* 2024).

Minerals and vitamins

Two billion people worldwide lack adequate iron and zinc in their diets, a problem called hidden hunger. Rice biofortification, breeding varieties with higher mineral content, offers one solution. Nepalese landraces show promising variation for these traits (Senguttuvel *et al.,* 2023). Iron content in brown rice ranges from 2.8 to 24.6 mg per kilogram across different varieties. Kalo Nuniya stands out with the highest iron levels, making it an obvious candidate for breeding programs. Zinc content varies even more widely, from 16.2 to 58.4 mg per kilogram. Several landraces exceed the target of 28 mg per kilogram set by HarvestPlus, the international program working to breed more nutritious crops. These include Rato Anadi at 45.2 mg/kg, Pokhreli Jethobudho at 38.6 mg/kg, and Seto Bageri at 34.8 mg/kg. Protein content ranges from 7.2% to 12.8%, with mountain varieties generally having more protein due to cooler growing conditions (Bhandari *et al.,* 2017).

Antioxidants in colored rice

The red, purple, and black colors in some Nepalese rice varieties come from anthocyanins, the same compounds that make blueberries blue and red wine red. These pigments act as antioxidants that may help prevent chronic diseases. Red rice varieties contain mainly cyanidin-3-glucoside, while purple and black varieties have more delphinidin-3-glucoside and peonidin-3-glucoside (Shao *et al.,* 2011; Chen *et al.,* 2024). Total anthocyanin content in colored landraces ranges from 80 to 420 mg per kilogram. When tested for antioxidant activity using the DPPH method, colored rice showed 65% to 85% free radical scavenging, much higher than white rice. This nutritional advantage has generated growing interest in colored rice both within Nepal and internationally.

Genetic diversity from DNA studies

Microsatellite marker analysis

Looking at DNA directly gives us a clearer picture of genetic diversity than physical traits alone. Microsatellite markers, also called simple sequence repeats or SSRs, have been the workhorse tool for this research (Dudhe, 2012). These short, repeated DNA sequences vary in length between individuals, making them useful for distinguishing varieties and measuring diversity. Studies of Nepalese landraces consistently find high genetic diversity. Expected heterozygosity, a standard measure for diversity studies, conducted earlier ranges from

0.42 to 0.78 depending on the collection examined (Neupane *et al.,* 2020; Poudel *et al.,* 2020; Dudhe *et al.,* 2024; Neupane and Regmi, 2020). Polymorphism information content averages around 0.68, indicating that these markers are highly informative for diversity work. Population structure analysis reveals clear genetic groupings that match geography and ecology. Landraces from the Terai lowlands cluster together and show more than 85% indica ancestry. Mountain varieties form a separate group with predominantly japonica background exceeding 75%. Hill zone landraces fall between these extremes with mixed ancestry, reflecting centuries of gene flow between the two subspecies (Shrestha *et al.,* 2024).

SNP analysis and genome studies

Newer technologies that examine single nucleotide polymorphisms, or SNPs, provide even finer resolution. Studies using arrays with thousands to tens of thousands of SNP markers have measured nucleotide diversity in Nepalese rice. The values, ranging from 0.0018 to 0.0032, match what researchers find in rice collections from other parts of Asia (Huang *et al.,* 2012; Wang *et al.,* 2018). Scientists have also conducted genome-wide association studies to connect specific DNA variants with important traits. These studies have identified regions on different chromosomes associated with grain length, amylose content, and cold tolerance (Bhattarai *et al.,* 2021).

Evolutionary relationships

Evolutionary relationships stues are important to understand the distinctness and similarity of the species. Building family trees from DNA data helps us understand how Nepalese landraces relate to each other and to rice from elsewhere. The analyses clearly separate indica and japonica lineages but also reveal varieties with intermediate positions that likely arose from ancient crosses between the two groups. Dating these divergences using molecular clock methods suggests that high-altitude japonica landraces split from lowland populations around 2,000 to 3,000 years ago, roughly when historical records indicate people were settling mountain valleys (Ahmadi *et al.,* 2023).

Conservation status and threats

Current conservation efforts

Nepal stores seeds from about 1,800 rice varieties at the National Agriculture Genetic Resources Centre. This sounds like a lot, but it represents only about 70% of the estimated 2,500 landraces that exist or recently existed in farmers' fields (Gauchan *et al.,* 2012). International gene banks hold even fewer Nepalese samples, leaving many unique varieties without backup storage anywhere. Community seed banks have become an important complement to official gene banks. These farmer-managed collections now operate in 78 districts across Nepal, together maintaining over 600 rice varieties. The Kachorwa community seed bank in Bara district keeps 127 varieties while the one in Begnas, Kaski district maintains 89 (Chaudhary *et al.,* 2013). These living collections allow continued natural selection and adaptation, something that frozen seeds in a vault cannot do.

Genetic erosion

The diversity that took thousands of years to develop has been shrinking rapidly. Surveys by Gauchan *et al.,* (2012) estimated that about one-third of landrace diversity disappeared in the three decades leading up to their study. When modern high-yielding varieties became available in the 1960s through 1980s, many farmers understandably adopted them for better yields. Today these modern varieties cover roughly 65% of Nepal's rice land.

Traditional landraces hang on mainly in marginal areas that modern varieties cannot handle, in remote mountain valleys, and in places where people specifically want traditional grain qualities. Climate change makes things worse. As temperatures rise, mountain varieties face the choice of moving uphill, which is often impossible, or dying out. Changes in rainfall patterns stress varieties adapted to traditional monsoon timing. Meanwhile, young people continue leaving rural areas for cities, taking their knowledge of traditional farming with them (Shrestha *et al.*, 2012).

Use in breeding programs

Pre-breeding work

Breeders have started tapping into the useful genes hidden in Nepalese landraces. Crosses between drought-tolerant landraces like Kalo Masino and high-yielding modern varieties have produced lines that yield 15% to 25% more than their parents when water is limited (Paneru *et al.*, 2018). Cold tolerance genes from Jumli Marsi have been moved into other backgrounds, allowing rice cultivation to expand into higher elevation areas that were previously too cold. DNA markers now help breeders select plants with desired traits more efficiently than was possible before.

Success stories

Two varieties released in Nepal show what landrace-based breeding can achieve. Chandannath-1 and Chandannath-3 came from crosses involving Jumli germplasm. They tolerate cold well enough to grow at 2,600 meters elevation while yielding 2.5 to 3.2 tons per hectare. Farmers adopting these varieties have expanded the rice-growing area in mountain districts by about 15%, improving food security in remote regions (Adhikari *et al.*, 2018). International programs have also benefited from Nepalese genetic material. Brown spot resistance genes from Nepalese landraces have been incorporated into breeding lines at the International Rice Research Institute (Rajan *et al.*, 2021).

Summary of genetic diversity data in a one frame

Table 1: Genetic diversity in Nepalese rice landraces from different studies

Study	**Markers**	**Samples**	**Expected heterozygosity**	**Polymorphism information content**	**Groups**
Neupane *et al.,*. (2020)	SSR	30	0.58-0.76	0.54-0.73	3
Poudel *et al.*, (2020)	RAPD+SSR	25	0.42-0.69	0.39-0.66	4
Shrestha *et al.*, (2024)	SNP	42	0.68-0.78	0.65-0.75	5
Bhattarai *et al.*, (2021)	GBS-SNP	68	0.71-0.82	0.68-0.79	6

Knowledge gaps and future directions

What we still need to learn

Most studies of Nepalese landraces have been done at single locations under controlled conditions. We lack good data on how these varieties perform across different environments and over years. This genotype by environment

Genome sequencing costs have dropped dramatically, but few Nepalese landraces have been fully sequenced. Techniques for measuring gene activity and metabolite profiles could reveal how these plants achieve their remarkable adaptations, but such studies are almost nonexistent.

Research priorities

Climate change makes understanding adaptation more urgent than ever. We need long-term studies tracking how landraces respond to changing conditions. Models combining climate projections with genetic information could help identify which varieties and which genes will matter most in the future (Ahmadi *et al.*, 2023). Participatory breeding that involves farmers directly offers another promising path. Farmers know their varieties and their local conditions intimately. Combining their knowledge with modern breeding tools could produce locally adapted varieties that farmers actually want to grow.

Building capacity

More Nepalese rice varieties need to be deposited in international gene banks for long-term safety. This requires collecting trips to remote areas, careful documentation, and formal deposit procedures. Stronger links between Nepalese researchers and international programs would benefit everyone. Building up local expertise in molecular biology, bioinformatics, and modern phenotyping will take time and investment but is essential for Nepal to fully benefit from its own genetic resources.

interaction matters enormously for practical breeding but testing it requires resources that have been scarce. Different research groups have used different methods, making it hard to compare results across studies (Subedi *et al.*, 2024). Modern tools for studying plants have barely been applied to Nepalese rice. Drones with specialized cameras could measure growth and stress responses across whole fields.

Conclusion

Nepalese rice landraces represent thousands of years of careful selection by generations of farmers working in challenging and diverse environments. The research reviewed here shows that this effort produced remarkable genetic diversity. Plant architecture, growth timing, grain properties, stress tolerance, and nutritional value all vary widely across the roughly 2,500 varieties that have been identified. Varieties like Kalo Masino and Seto Bageri tolerate drought that would devastate ordinary rice. Jumli Marsi grows where most rice cannot survive the cold. Kalo Nuniya packs more minerals than typical rice. These are not just interesting facts for scientists. They represent practical resources for feeding people as climate change makes farming harder. DNA studies confirm and extend what we can see with our eyes. Genetic diversity is high, with clear structure reflecting geography and ancestry from both indica and japonica rice. This mixed heritage gives Nepalese landraces unique genetic combinations not found elsewhere. Success stories like the cold-tolerant Chandannath varieties and the incorporation of disease resistance into international breeding programs prove that this diversity has practical value. But these resources face real threats. About one-third of the diversity that existed a few decades ago has already vanished. Modern varieties continue replacing traditional ones. Climate change pushes mountain varieties toward extinction. Young people leave rural areas. Each variety that disappears takes with its genes that might have helped solve problems we cannot yet foresee.

What needs to happen is clear even if achieving it is not easy. We need to complete the collection and characterization of remaining landraces before more disappear. Both gene bank storage and living conservation in farmers' fields must be strengthened. Modern genetic tools should be applied more widely. Breeding programs should make better use of landrace genes. And all this needs to happen with appropriate benefit sharing so that the communities who maintained this diversity for generations are not left out as others profit from it. The stakes are high. Rice feeds half the world, and Nepalese landraces carry genetic keys that could help rice production adapt to a changing climate.

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