Plant Archives Vol. 25, Supplement 2, 2025 pp. 2415-2428 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.supplement-2.307

THE IMPORTANCE OF LANDRACES IN THE PRESENT CONTEXT OF CLIMATE CHANGE IN INDIA: A REVIEW

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(Date of Receiving : 15-04-2025; Date of Acceptance : 21-06-2025)

ABSTRACT

Landraces, the traditional crop varieties shaped by centuries of natural selection and farmer-driven breeding, are invaluable in tackling the challenges posed by climate change. These genetically unique crops show impressive resilience to local environmental stressors like drought, salinity, heat, and flooding, making them essential for sustainable agriculture amid unpredictable weather patterns. This paper examines the role of landraces in adapting to climate change, with a focus on rice, millet, vegetable, and pulse landraces across India. It emphasizes how varieties like Pokkali rice in saline coastal regions and Kodo millet in drought-prone areas provide solutions to agricultural systems facing climate-related pressures. Additionally, the paper explores how landraces can enhance crop improvement programs by incorporating their resilient traits into modern varieties. To fully harness the potential of landraces, the paper advocates for focused research on phenotyping, genomic analysis, and climate projections, as well as policy changes to support better seed regulations, farmer rights, and institutional frameworks. In conclusion, landraces offer a sustainable way forward, integrating traditional agricultural wisdom with contemporary scientific methods to promote food security and resilience in the face of global climate challenges.
***Keywords*: Climate change, Landraces and Traditional crop varieties.**

Introduction

India, with its rich tapestry of agro-ecological regions from the Himalayan highlands to the coastal plains has served as a cradle of agricultural biodiversity for thousands of years. Across these diverse landscapes, traditional farming communities (Calvet-Mir *et al.*, 2018) have cultivated and preserved a vast array of locally adapted crop varieties known as landraces. These landraces, shaped by generations of farmer-led selection and natural evolution, are more than just seeds. They embody indigenous knowledge, ecological harmony, and genetic strength (Villa, 2005; Calvet-Mir *et al.*, 2018). As climate change increasingly disrupts India's agricultural systems bringing erratic rainfall, temperature fluctuations, more frequent extreme weather events, and altered cropping patterns, the country's farming sector is confronted with mounting risks (Di Falco and Chavas, 2008). According to the Intergovernmental Panel on Climate Change (IPCC), India stands among the nations most vulnerable to climate impacts, with crop productivity potentially dropping by 10–40% between 2080 and 2100 unless adaptive strategies are implemented.

Amid this growing climate uncertainty, the genetic wealth held within India's landraces emerges as a crucial, yet frequently underutilized-tool for building resilience in agriculture. Unlike modern high-yielding varieties that are bred for performance in controlled or ideal conditions, landraces have naturally adapted to their local environments, often exhibiting extraordinary tolerance to various stresses (Shroyer and Cox, 1993). Their inherent diversity and environmental fit make them powerful allies in the quest for climate-resilient farming. The current review highlights the pivotal role of landraces in India's climate adaptation efforts by exploring their unique traits, current conservation status, and potential contributions to sustainable agriculture. It contends that protecting and promoting the use of landraces is not just about safeguarding cultural heritage—it is a strategic imperative for ensuring long-term food security and ecological sustainability in the face of climate change (Altieri, 2009).

Understanding Landraces: Characteristics and Significance

Concept and Characteristics

Landraces are plant populations that have evolved over multiple generations through the interplay of natural selection and traditional farming methods. Unlike modern crop varieties, which are bred for genetic uniformity, landraces are marked by considerable genetic diversity within a single population. This variability is a result of selection focused not on uniformity, but on maintaining stable yields and resilience in specific local environmental conditions (Zeven, 1998; Casañas *et al.*, 2017).

Key traits that set landraces apart include:

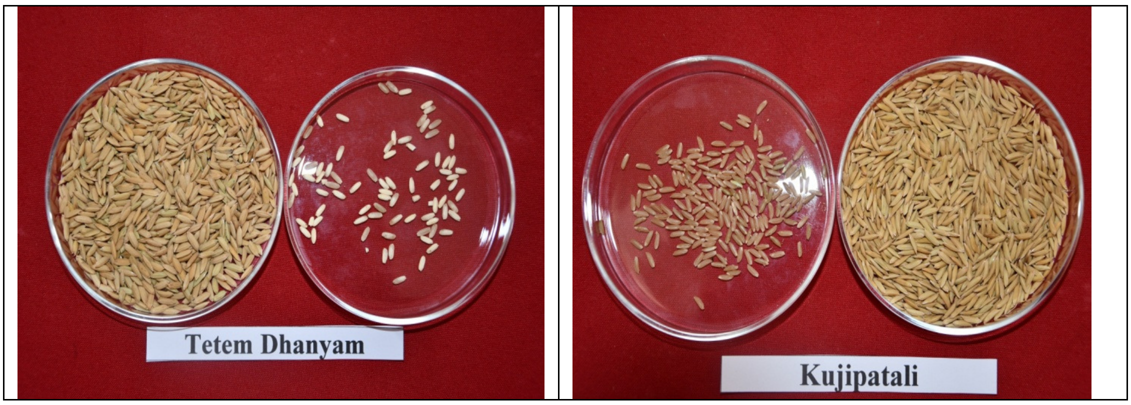
1. **Genetic Variability**: Landraces are composed of a wide array of genetic types, making them genetically diverse populations rather than uniform cultivars. This internal diversity enables them to respond flexibly to environmental shifts (FAO, 2019).
2. **Adaptation to Local Conditions**: Having co-evolved with specific regional climates, soils, pests, and diseases, landraces are well-suited to thrive in diverse agro-ecological zones especially in areas where commercial varieties often underperform (Altieri *et al.*, 2015; Altieri & Nicholls, 2017; Ma *et al.*, 2021).
3. **Capacity for Ongoing Evolution**: The broad genetic base allows landraces to continue evolving in response to environmental pressures, making them particularly valuable in adapting to the unpredictable effects of climate change.
4. **Nutritional Richness**: Many landraces offer enhanced nutritional value, often containing greater concentrations of essential micronutrients, antioxidants, or proteins compared to modern high-yield varieties bred mainly for quantity.

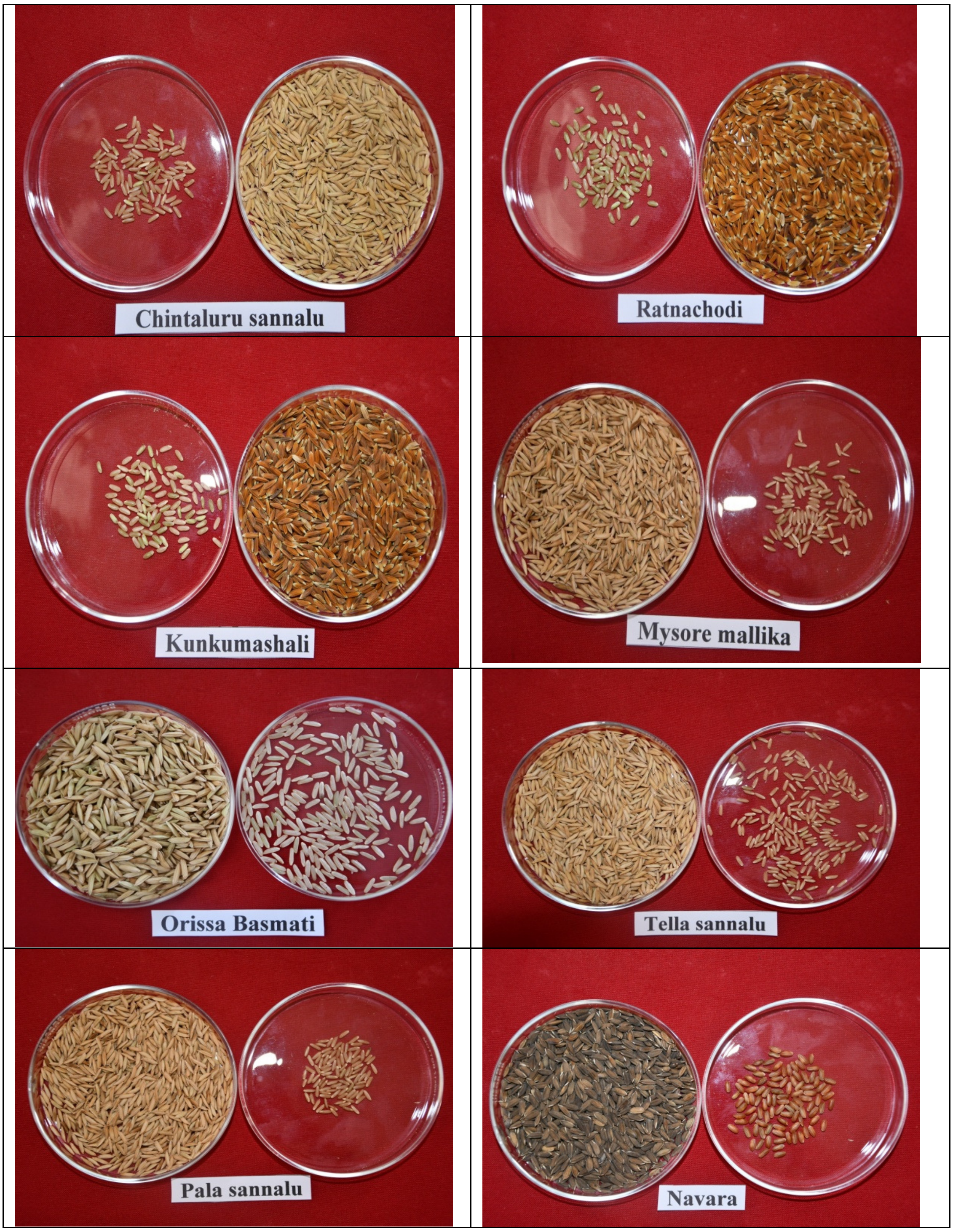
India's Indigenous Crop Legacy

India is globally recognized as one of the richest reservoirs of agricultural biodiversity and is designated as a Vavilovian center for the origin and diversification of crops. The nation's vast geographic range, encompassing varied landscapes, climates, and cultural traditions, has given rise to a remarkable diversity of landraces across numerous crop species.

Examples of India's Landrace Diversity Include:

1) **Rice**: India is home to more than 100,000 rice varieties, including those adapted to extreme conditions such as salt-tolerant types from coastal regions, drought-resilient varieties from rainfed zones (Yogameenakshi *et al.*, 2003; Mishra *et al.*, 2018; Beena *et al.*, 2021), and deep-water types suited to flood-prone areas (Ismail *et al.*, 2013; Biswajit *et al.*, 2017; Sarangi *et al.*, 2020). Prominent examples include Pokkali (salt-tolerant) from Kerala, Kalanamak (drought-tolerant) from Uttar Pradesh, and submergence-tolerant varieties like Jhilli and Jabra from Odisha. Some veteran local landraces of paddy were dipicted in Fig 1

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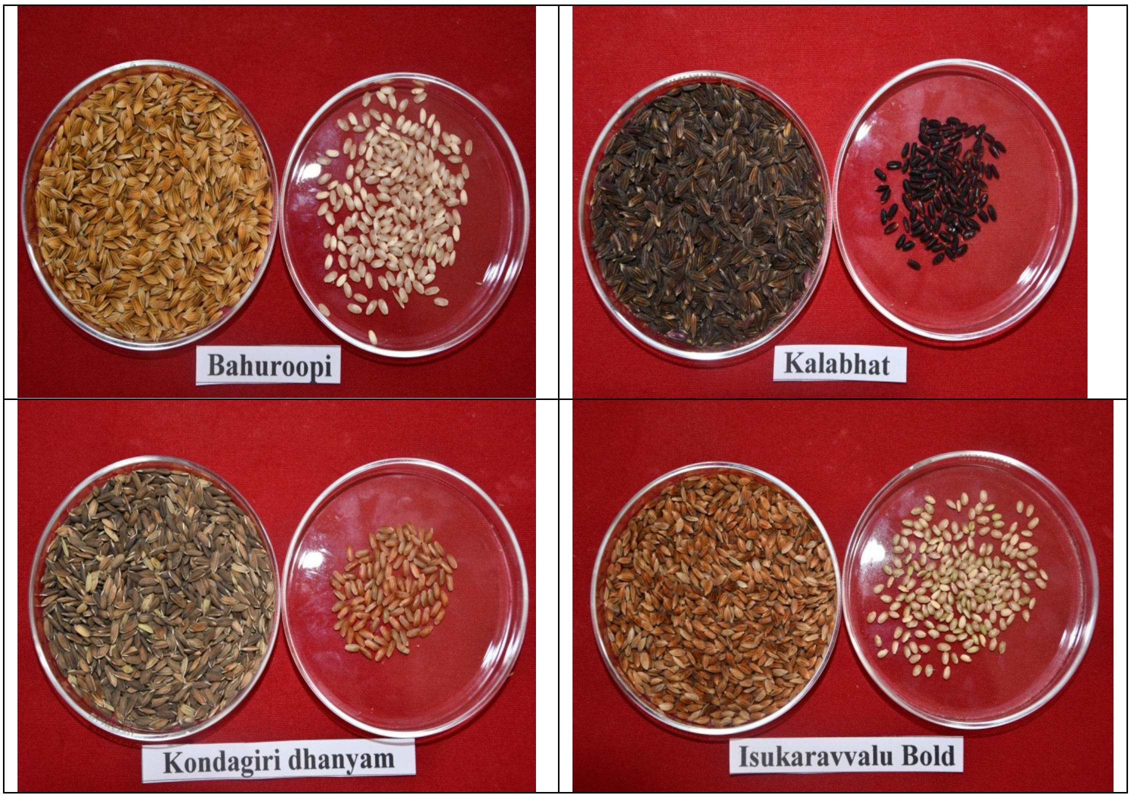

Fig. 1 : Local landraces of paddy

2) **Millets**: Indigenous millet landraces such as finger millet, sorghum, and pearl millet (Blum and Sullivan, 1986; Yadav, 2010; Srivastava *et al.*, 2022) have evolved exceptional tolerance to drought and low-fertility soils (Tadele, 2016). Millets grown in Rajasthan's desert regions are particularly efficient at surviving on minimal rainfall.

3) **Pulses**: Traditional landraces of legumes like chickpea and pigeonpea possess diverse resistances to diseases, heat, and water stress (Revanappa *et al.*, 2025). Heat-tolerant chickpea varieties from central India are especially noteworthy (Rana *et al.*, 2016; Dhole *et al.,* 2024).

4) **Vegetables**: Indigenous varieties of brinjal (eggplant), okra, gourds, and leafy greens are well-suited to regional pests, diseases, and specific climatic challenges (Perez *et al.*, 2015; Dhaliwal and Sharma, 2016).

5) **Fruit Crops**: Native cultivars of mango, jackfruit, citrus, and other fruits reflect generations of farmer-led selection for taste, resilience to pests, and local adaptation (Grigoriou, 2020; Lazaridi *et al.*, 2024).

This extensive diversity of landraces, shaped through centuries of traditional knowledge and selective cultivation, has historically offered a buffer against environmental unpredictability.

Climate Change Challenges for Indian Agriculture

Current and Projected Climate Impacts

India's agricultural sector, which provides livelihoods for nearly 60% of the population and contributes around 18% to the nation's GDP, is highly susceptible to the impacts of climate change. Already under pressure, the sector faces a range of emerging challenges:

i. **Shifting Rainfall Patterns**: The monsoon has become increasingly unpredictable, with inconsistent timing, duration, and intensity. Some areas endure extended dry periods, while others are hit by heavy downpours that result in flooding (Wani *et al.*, 2009; Singh *et al.*, 2019; Pathak, 2023).

ii. **Rising Temperatures**: Average temperatures in India have climbed by about 0.7°C over the past century, and projections estimate an increase of 1.5 to 4.3°C by the end of the 21st century. Such temperature rises are particularly detrimental to crops like wheat and rice, which show significant yield reductions once specific thermal thresholds are crossed (Aggarwal, 2008; Rao *et al.*, 2014).

iii. **Increased Frequency of Extreme Events**: India is witnessing a rise in extreme climatic occurrences such as cyclones, droughts, floods, and heatwaves. Notably, between 2018 and 2019, the country experienced devastating floods in Kerala, prolonged droughts in Maharashtra, and record-breaking heatwaves in northern regions (Sikka, 2016; Ray *et al.*, 2019; Sivakumar, 2020).

iv. **Water Scarcity**: Depleting groundwater reserves, coupled with irregular rainfall, are intensifying water shortages in many farming areas. Given that nearly 60% of India's farmland is rainfed, erratic precipitation patterns pose a serious threat to agricultural productivity (Dhawan, 2017; Selvan *et al.*, 2021).

v. **Changing Pest and Disease Patterns**: Climate change is reshaping the distribution and behavior of pests and crop diseases. Warmer temperatures are facilitating the spread of new pests and pathogens, complicating pest management and crop protection efforts (Tiwari, 2024; Li *et al.*, 2025).

Fragility of Modern Crop Genotypes

Since the Green Revolution, modern high-yielding varieties (HYVs) have played a central role in ensuring India's food security. However, these varieties are particularly vulnerable to the impacts of climate change due to several inherent limitations:

1. **Genetic Narrowness**: Most HYVs are developed from a limited genetic pool, making them highly prone to new pests, diseases, and environmental fluctuations. Their performance often collapses under non-ideal conditions (Azeez *et al.*, 2018; Thanopoulos *et al.*, 2024).
2. **High Input Dependence**: These varieties typically rely heavily on stable and abundant inputs like fertilizers, pesticides, and irrigation resources that are increasingly affected by climate variability (Lehikoinen *et al.*, 2021; Sandstrom *et al.*, 2024).
3. **Restricted Adaptability**: Designed for specific agro-climatic zones, HYVs generally lack the flexibility to perform well under varying environmental conditions, which are becoming more unpredictable with climate change (Lyon *et al.*, 2024; Han *et al.*, 2024).
4. **Physiological Limitations**: Many modern varieties have been optimized for yield under ideal circumstances rather than resilience, leaving them physiologically ill-equipped to cope with stressors like drought (Begna, 2020), heat, or excess water (Inostroza *et al.*, 2021).

These weaknesses become starkly visible in climate-affected regions. For example, during the 2015–2016 drought in Maharashtra, HYV rice varieties suffered yield declines of 40–60%, while traditional drought-tolerant landraces experienced only 15–30% losses. Similarly, in the 2019 Bihar floods, deep-water rice landraces demonstrated far better survival rates compared to their modern counterparts.

Ecological Adaptations of Landraces to Climate Variability

1) Drought Tolerance Mechanisms

Numerous Indian landraces display exceptional drought tolerance, achieved through a range of physiological and morphological traits:

a) **Root System Development**: Many landraces possess deep and expansive root structures that enable them to tap into moisture reserves in lower soil layers (Sofi *et al.*, 2021; Ranjan *et al.,* 2022). For example, traditional rice varieties from eastern India can develop roots extending 1 to 1.5 meters deep, in contrast to the 0.5–0.8 meters typically found in modern varieties (Al-Naggar *et al.*, 2019).

b) **Efficient Water Use**: Certain landraces are highly efficient in water usage, generating greater biomass with minimal water input. Traditional millet crops like kodo and little millet, for instance, can yield well with only 200–300 mm of annual rainfall (Tardieu, 2022; Zhang *et al.*, 2022).

c) **Flexible Growth Duration**: Many landraces exhibit adaptable growth timelines, enabling them to complete their life cycle during brief periods of adequate moisture. 'Navara' rice from Kerala, for instance, matures in just 60–70 days, compared to the 120–150 days required by modern varieties (Amelework *et al.,* 2015; Grossman, 2023).

d) **Physiological Drought Resistance**: Some landraces are equipped with internal mechanisms to withstand water stress, such as osmotic regulation, enhanced membrane stability, and elevated antioxidant activity, all of which help reduce damage caused by drought-related oxidative stress (Badigannavar *et al.*, 2018; Missanga *et al.*, 2021).

2) Heat Tolerance Traits

As global temperatures rise, heat tolerance becomes essential for crop survival and productivity. Indian landraces exhibit various adaptations to high-temperature conditions:

a) **Reproductive Thermotolerance**: Some landraces maintain pollen viability and fertilization capacity even at temperatures that cause sterility in modern varieties. For instance, traditional rice varieties from central India can still set grain when temperatures surpass 38°C during flowering (Priya *et al*., 2018; Beena *et al*., 2025).

b) **Leaf Adaptations**: Morphological features like waxy leaf surfaces, leaf rolling, and pubescence help reduce transpiration and keep leaf temperatures lower. These adaptations are particularly visible in landraces from arid regions (Khan *et al*., 2019; Zhang *et al*., 2020).

c) **Cellular Protection Mechanisms**: Some landraces produce heat shock proteins and other protective compounds that shield cells from damage during high temperatures (Priya *et al*., 2018; Arachchige *et al*., 2024).

d) **Nocturnal Recovery**: Certain landraces recover more effectively from heat stress during cooler nighttime temperatures, helping them maintain growth despite the heat during the day (Porch *et al*., 2013)

3) Flooding and Waterlogging Tolerance

In flood-prone regions, landraces have evolved remarkable mechanisms to survive excessive water:

a) **Elongation Ability**: Deep-water rice landraces from the Ganges-Brahmaputra basin can stretch their stems by up to 25 cm per day during flooding, allowing their leaves to stay above the water (Ahmed *et al*., 2013).

b) **Submergence Tolerance**: Some rice landraces carry the SUB1 gene, which allows them to endure full submergence for up to 10-14 days. This trait has been transferred to some modern varieties (Ahmed *et al*., 2013).

c) **Aerenchyma Formation**: Flood-tolerant landraces develop specialized tissue known as aerenchyma, which helps transport oxygen to the roots under waterlogged conditions (Huang, 2022).

d) **Adventitious Root Formation**: During flooding, many landraces develop adventitious roots from stem nodes, enhancing their ability to absorb nutrients and oxygen (Ahmed *et al*., 2013; Basavaraj *et al*., 2024)

4) Pest and Disease Resistance

With climate change affecting pest and disease dynamics, resistance traits have become more critical:

a) **Durable Resistance**: Unlike modern varieties, which often rely on single-gene resistance, many landraces exhibit polygenic resistance that remains effective against evolving pest populations (Stuthman *et al*., 2007; Marone *et al*., 2021).

b) **Diverse Resistance Mechanisms**: Landraces employ various strategies to defend against pests, including physical barriers (such as trichomes and wax layers), chemical defenses (alkaloids, phenolics) (Mier *et al*., 2018; Marone *et al.*, 2021), and plant architecture that supports beneficial organisms.

c) **Induced Resistance**: Certain landraces show superior induced resistance, activating defense systems in response to pest or pathogen attacks (Mier *et al.*, 2018; Wani *et al*., 2022).

d) **Microbiome Associations**: Landraces often form beneficial associations with soil microorganisms that enhance disease resistance through processes like induced systemic resistance (Roy *et al.*, 2021; Wani *et al*., 2022).

5) Nutritional Resilience

Climate change can affect both crop yields and nutritional quality. Many landraces maintain superior nutritional profiles that remain stable even under stressful conditions:

a) **Micronutrient Density**: Traditional varieties often contain higher levels of essential micronutrients compared to modern varieties. For example, colored rice landraces are significantly richer in antioxidants and minerals (Marone *et al*., 2021; Yadav *et al*., 2024).

b) **Protein Content Stability**: Some landraces retain their protein content even under stress conditions that typically reduce protein levels in modern varieties (Dwivedi *et al*., 2016).

c) **Secondary Metabolite Production**: Many landraces produce higher amounts of beneficial secondary metabolites (such as flavonoids and phenolics) when exposed to environmental stress, which can actually enhance their nutritional value (Dwivedi *et al*., 2016)

These diverse traits make landraces valuable resources for developing climate-resilient agriculture. Their adaptations, refined over centuries of natural and farmer-driven selection, offer practical solutions to contemporary environmental challenges.

Current Status and Threats to Landrace Conservation

1. Erosion of Agricultural Biodiversity

Despite their significant potential, India's landrace diversity is undergoing severe erosion. Several factors contribute to this concerning trend:

a. **Agricultural Modernization**: The Green Revolution's focus on high-yielding varieties has led to the widespread replacement of landraces. In regions like Punjab-Haryana, which once boasted hundreds of wheat landraces, more than 90% of wheat cultivation now relies on just 5-10 modern varieties.

b. **Market Pressures**: The demand for standardized products and the integration of agriculture into global supply chains have marginalized many landraces, despite their superior taste or nutritional qualities, as they do not meet uniform appearance standards.

c. **Policy Biases**: Agricultural policies, such as subsidies and procurement systems, have historically favored modern varieties over landraces, creating economic disincentives for farmers to maintain traditional varieties.

d. **Knowledge Erosion**: Traditional knowledge systems, including those related to landrace cultivation and uses, are being lost as farming communities age and lifestyles change (Calvet-Mir *et al.*, 2011).

e. **Climate Change**: While landraces offer potential solutions to climate change, rapidly changing conditions sometimes outpace their adaptive capacity, leading to their abandonment when they fail to cope (Ma *et al.*, 2021).

2. Institutional Challenges

Efforts to conserve landraces face significant institutional hurdles:

a. **Ex-situ Conservation Limitations**: Although India has established significant gene bank collections through institutions like the National Bureau of Plant Genetic Resources (NBPGR), many landraces remain underrepresented or uncollected. Moreover, gene bank conservation often isolates varieties from their evolutionary context, limiting their ability to adapt further.

b. **In-situ Conservation Gaps**: Programs for on-farm conservation of landraces are limited in scope and funding, especially in comparison to modern breeding programs (Veteläinen, 2009; Raggi, 2022).

c. **Intellectual Property Issues**: The lack of proper recognition of farmers' rights and their contributions to the development of landraces has led to tensions over ownership, access, and benefit-sharing of genetic resources.

d. **Data Gaps**: Insufficient documentation of landrace traits, especially those relevant to climate resilience, hampers their effective use in breeding programs.

e. **Coordination Challenges**: Conservation efforts often suffer from poor coordination between government bodies, research institutions, NGOs, and farming communities.

Successful Conservation Initiatives

Despite these challenges, some initiatives have demonstrated successful conservation strategies:

- **Community Seed Banks**: Organizations like the Deccan Development Society in Telangana and Navdanya in Uttarakhand have set up community-managed seed banks that conserve numerous local varieties while keeping them actively cultivated.
- **Participatory Plant Breeding**: Projects such as those by the MSSRF in the Kolli Hills involve farmers in breeding programs, which strengthen landraces while preserving their adaptive traits (Marone *et al.*, 2021).
- **Geographical Indication Protection**: Several landraces, such as Basmati and Navara rice, have been granted geographical indication status, creating market incentives for their conservation.
- **Indigenous Knowledge Documentation**: Initiatives like the People's Biodiversity Registers help preserve traditional knowledge about landraces, incorporating it into broader conservation strategies.
- **Market Development**: Groups like Sahaja Samrudha in Karnataka have created specialty markets for traditional varieties, generating economic incentives for their continued cultivation.

These successful examples show that effective conservation requires holistic approaches that address the biological, cultural, economic, and policy aspects of landrace preservation (Riu-Bossoms *et al.*, 2014).

Landraces in Climate Adaptation Strategies

1. Breeding for Climate Resilience

Landraces provide valuable genetic resources for developing climate-resilient crops through several approaches:

- **Trait Mining**: Evaluating landraces for climate-relevant traits can uncover useful genes for breeding programs. For instance, the submergence tolerance gene SUB1 was discovered in an Indian rice landrace and successfully transferred to widely cultivated varieties.
- **Evolutionary Breeding**: Rather than focusing on individual traits, evolutionary breeding maintains diverse populations under specific stress conditions, allowing natural selection to enhance adaptation over generations (Azeez, 2018). Dr. Debal Deb's work at Basudha Farm in Odisha exemplifies this approach, adapting rice landraces to changing conditions.
- **Participatory Varietal Selection**: Involving farmers in the selection and evaluation of varieties under local conditions helps identify landraces that thrive in specific micro-environments. Programs like MSSRF's coastal Tamil Nadu project have used this approach to select salt-tolerant rice landraces.
- **Genomic Tools**: Advanced genomic techniques enable the efficient identification of valuable traits from landraces. The C4 Rice Project, for example, seeks to improve photosynthetic efficiency by using genetic diversity from traditional varieties.
- **Pre-breeding**: Developing intermediate breeding lines that incorporate landrace traits can bridge the gap between conservation and practical use.

2. Diversification and Risk Management

Beyond their genetic contributions, landraces offer opportunities for agricultural diversification:

- **Mixed Cropping Systems**: Traditional farming systems often involve cultivating multiple landraces together, reducing risk by spreading stress tolerance across different varieties. This method is being revived in projects like the Integrated Tribal Development Project in Odisha.
- **Crop Rotations**: A diverse portfolio of landraces allows for more complex crop rotations, improving soil health and breaking pest cycles—practices that are particularly beneficial under climate change.
- **Landscape Diversification**: Distributing various landraces across landscapes based on micro-environmental variations can improve overall productivity and resilience.
- **Temporal Diversification**: Maintaining landraces with varying growth durations allows farmers to adjust planting schedules in response to changing seasonal patterns.

3. Integration with Modern Technologies

Landraces can be integrated with modern agricultural technologies to maximize their benefits:

- **Precision Agriculture**: Digital tools can help optimize landrace deployment based on soil, water, and microclimate conditions.
- **Climate Modeling**: Combining climate projections with landrace trait databases can match varieties to future conditions in different regions.
- **Microbial Inoculants**: Pairing landraces with beneficial microorganisms can boost their stress tolerance and productivity.
- **Water Management Technologies**: Integrating water-efficient landraces with modern irrigation systems can enhance water use in drought-prone areas.

4. Policy and Institutional Frameworks

For landraces to be effectively utilized, supportive policies are essential:

- **Farmers' Rights**: Strengthening the implementation of farmers' rights under the Protection of Plant Varieties and Farmers' Rights Act can incentivize landrace conservation and improvement (De et al., 2021).
- **Certification Systems**: Creating certification systems for landrace products can help build premium markets that support their ongoing cultivation.
- **Public Procurement**: Including landraces in public procurement programs, especially for nutritional security, can create stable demand for them.
- **Research Funding**: Increased investment in landrace research, particularly focusing on climate-resilient traits, can expedite their integration into adaptation strategies.
- **Extension Services**: Expanding extension services to include knowledge on landrace cultivation will facilitate their wider adoption

Case Studies: Landraces in Climate Adaptation

1. **Rice Landraces in Coastal Salinity**

The coastal regions of Odisha, West Bengal, and Kerala are increasingly facing salinity due to rising sea levels and storm surges. In these areas, salt-tolerant rice landraces exhibit remarkable climate resilience:

- **Pokkali Rice (Kerala)**: Known for tolerating salinity levels up to 8-10 dS/m, this landrace thrives where modern varieties struggle. Its unique salt-exclusion mechanisms and tall stature allow it to grow in deep water, making it especially valuable in salinized coastal regions. The Pokkali system, which alternates rice cultivation with shrimp farming, exemplifies a climate-adaptive integrated farming approach.
- **Gheen Sali (Odisha)**: This variety can endure moderately saline conditions, which can reduce yields of modern rice varieties by 50-80%. Farmers in Bhitarkanika have preserved this variety, recognizing its reliability in the face of growing salinity.
- **Nonabokra (West Bengal)**: This rice landrace tolerates both salinity and flooding, making it particularly useful in delta regions affected by both salinity intrusion and seasonal flooding.

Efforts to maintain and enhance these landraces have included collaborations between local farmers and institutions such as the Central Rice Research Institute and the M.S. Swaminathan Research Foundation.

2. **Millets in Drought-Prone Regions**

In peninsular India, where rainfall is becoming more erratic, traditional millet landraces exhibit impressive drought resilience:

- **Kodo Millet (Madhya Pradesh)**: Local kodo millet varieties require as little as 200-250 mm of rainfall to yield crops, thriving where most other crops fail. In the Balaghat region, these millets have been crucial in maintaining food security during drought years when other staple crops like rice and wheat fail.
- **Ragi (Finger Millet) Diversity (Karnataka)**: The Western Ghats region preserves over 100 finger millet varieties, each exhibiting different drought tolerance mechanisms. For example, the Pichakadumila variety matures in just 70-80 days, allowing it to grow during brief periods of favorable moisture.
- **Little Millet (Chhattisgarh)**: Traditional varieties grown in the Bastar region are able to extract moisture from the soil in ways that allow them to thrive even in drought conditions, unlike other crops that succumb to wilting

Research and initiatives like the Millet Revival Project in Karnataka are helping to promote these drought-resistant crops by creating market linkages.

3. **Vegetable Landraces Under Heat Stress**

Rising temperatures across India have highlighted the importance of heat-tolerant vegetable landraces:

- **Brinjal (Eggplant) Landraces (Tamil Nadu)**: Varieties like Thiruthuraipoondi Kathiri can maintain fruit set at temperatures above 38°C, where commercial hybrids would typically experience flower drop. These landraces demonstrate superior pollen viability under heat stress.
- **Chili Varieties (Rajasthan)**: Local chili varieties from the Thar Desert are heat-tolerant, continuing to yield fruits even under harsh conditions that cause significant yield loss in commercial varieties.
- **Indigenous Leafy Vegetables**: Species like Chenopodium album (bathua) and Amaranthus exhibit greater heat tolerance than commercial vegetables like spinach, maintaining nutritional value even in high temperatures

The National Bureau of Plant Genetic Resources is documenting these heat-resistant varieties, while organizations like Navdanya and urban farming initiatives in cities like Bengaluru are promoting their cultivation.

4. **Pulses in Variable Rainfall Zones**

Pulses, crucial for both nutrition and soil health, face challenges due to fluctuating rainfall patterns. However, traditional pulse landraces offer important adaptations:

- **Horsegram Varieties (Karnataka)**: Local horsegram landraces are known for their drought tolerance, thriving where other pulses fail. These varieties possess extensive root systems and efficient water-use mechanisms.
- **Pigeon Pea Diversity (Maharashtra)**: The Western Ghats region preserves a variety of pigeon pea landraces with differing maturity periods, allowing farmers to match varieties to the expected rainfall in a given year.
- **Cowpea Landraces (Gujarat)**: Cowpea varieties from Gujarat exhibit remarkable recovery after

mid-season droughts, resuming growth and forming pods once the rains return.

These examples show that landraces are more than just remnants of agricultural history; they are practical solutions to present climate challenges. Their resilience, built over centuries of adaptation to local environments, can be key to modern climate adaptation strategies.

Future Directions and Recommendations

1. Research Priorities

To fully leverage the potential of landraces in climate adaptation, several research priorities should be addressed:

- **Systematic Phenotyping**: Evaluating landraces for climate-relevant traits using both field and controlled environment methods will help identify valuable genetic resources.
- **Genomic Characterization**: Applying advanced genomic tools to understand the genetic foundation of climate resilience in landraces would improve their use in breeding programs.
- **Climate Modeling Integration**: Integrating climate models with landrace distribution and trait data can help match varieties to regions projected to face specific climate conditions in the future.
- **Participatory Research**: Involving farmers in research ensures that findings are relevant and integrates traditional knowledge with modern scientific approaches.
- **Socioeconomic Studies**: Research on market development, value chains, and policies supporting landrace promotion will address economic challenges hindering their widespread adoption.

2. Policy Recommendations

To enhance landrace conservation and utilization, the following policy changes are recommended

- **Revise Seed Legislation**: Modifying seed certification standards to account for the inherent variability of landraces would facilitate their legal marketing.
- **Strengthen Farmers' Rights**: Better implementation of the Protection of Plant Varieties and Farmers' Rights Act would provide stronger recognition and support for farmers contributing to landrace development.
- **Integrate Landraces into Climate Policy**: Including landrace conservation and utilization in national and state climate adaptation strategies would increase funding and prioritize these efforts.
- **Create Economic Incentives**: Establishing payments for agrobiodiversity conservation services could incentivize farmers to maintain landraces.
- **Reform Agricultural Subsidies**: Redirecting agricultural subsidies toward supporting diversified farming systems would align economic incentives with climate resilience goals.

3. Institutional Strengthening

Several institutional improvements could enhance the conservation and use of landraces:

- **Coordination Mechanisms**: Improved coordination between research institutions, conservation organizations, extension services, and farming communities would enhance the effectiveness of landrace initiatives.
- **Capacity Building**: Strengthening agricultural extension services would improve support for landrace cultivation and adoption.
- **Community Institutions**: Supporting community-managed seed banks, farmer producer organizations, and participatory guarantee systems would empower local management of landrace resources.
- **Public-Private Partnerships**: Collaborations between public research institutions and private sector actors could accelerate the development and dissemination of improved varieties based on landrace traits.
- **International Collaboration**: Strengthening international partnerships, such as with the Crop Trust and the International Treaty on Plant Genetic Resources for Food and Agriculture, would provide additional resources and expertise

4. Education and Awareness

To support the conservation and use of landraces, awareness and education initiatives should be strengthened:

- **Agricultural Education**: Including landrace conservation in agricultural curricula would build capacity among future professionals.
- **Consumer Awareness**: Raising awareness about the nutritional, cultural, and environmental benefits of landrace products would create market demand.

- **School Programs**: Introducing agrobiodiversity education into school curricula would help future generations appreciate agricultural heritage.
- **Media Engagement**: Using media to highlight success stories of landrace utilization would increase public support.
- **Digital Platforms**: Developing digital platforms for sharing information about landraces would increase accessibility for younger generations.

Conclusion

Landraces represent not only a connection to agricultural heritage but also a vital resource for addressing future food security and agricultural sustainability. Their genetic diversity, local adaptations, and evolutionary potential offer essential tools for creating climate-resilient agricultural systems. Preserving and utilizing landraces requires integrated approaches that combine conservation, research, policy, and market development. By embracing both traditional knowledge and modern agricultural science, India can use its agricultural heritage to meet the challenges posed by climate change, ensuring resilience while preserving the cultural and biological diversity that has long supported Indian farming systems.

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