Scientia Review

Role of Molecular Breeding in Rice Improvement

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Abstract

More than half of the global population depends on rice as the main staple food and rice is an essential ingredient in the world food and nutritional security. Nevertheless, climate change, new pests and diseases, scarcity of water and rising population pressure are the real problems that are threatening the rice production even today. Traditional breeding strategies like those that have been successful in previous years tend to be time consuming and less specific in the complex characteristic representation. Molecular breeding is now an effective solution that makes the rice improvement programs more efficient and precise. Through the DNA markers, markers-assisted selection (MAS), gene pyramiding, genomic selection and genome editing methods, the breeders can manage to detect and introduce desirable genes at a very early stage in crop breeding. These sophisticated methods allow coming up with high yield, disease-resilient, climate-resistant and nutrient-enriched types of rice. Molecular breeding does not only speed up the breeding of varieties but it also enhances sustainable and environmentally-friendly farming. The key molecular tools applied in rice improvement, recent developments, and the future of precision breeding to ensure food security for the ever-increasing world population.

Keywords: Nutritional security, Markers-assisted selection, Genomic selection, Gene pyramiding

## Why rice improvement matters in the 21st century

More than half the world depends on rice as its staple. Rice is not only a staple food in such countries as India, China and most of the Southeast Asian countries but is intertwined with culture, economy, and rural livelihoods. Nevertheless, the growth of rice is currently challenged as never before:

- Global warming that leads to droughts and floods
- Due to natural selection, new races of pathogens emerged
- Reduction in water supplies
- Salinity of soil and soil erosion
- Increasing population which required more production

The traditional breeding techniques have been used to enhance the yield of rice over the decades. However, they are usually slow and even erratic. According to the changing climatic trends, accelerated breeding strategies are necessary in an era where climate is changing at a very fast rate.

This is the point where the molecular breeding
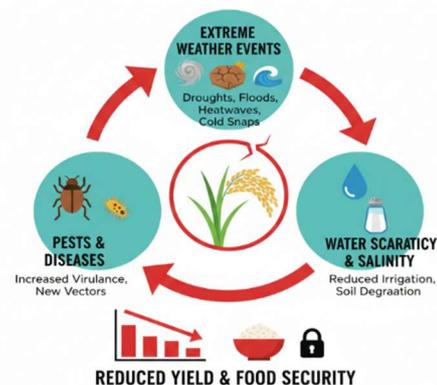
appears as an innovative approach.

Fig.1. Rice field challenges with multiple stress

From traditional breeding to molecular breeding

Farmers always picked out the most successful plant varieties since time immemorial, depending on the most noticeable characteristics such as yield, grain size or disease resistance. This is referred to as a conventional breeding process, which highly relies on the phenotypic selection.

Conventional: Pedigree, bulk methods for traits like tillering etc.

Limitations of traditional breeding:

- Time-consuming (8-12 years to release variety)
- Influenced by environmental factors
- Lack of ability to detect hidden superior character
- Limited precision in combining multiple genes

Molecular breeding is an improvement of the old breeding methods that involves the employment of DNA-based tools. Breeders do not choose plants only on the basis of their appearance but taking a closer look at their genetic makeup. This increases:

- ✓ Accuracy
- ✓ Speed
- ✓ Efficiency

What is Molecular Breeding?

Molecular breeding is the use of molecular markers and genomic tools to assist in plant selection.

All plants have DNA and the DNA would have genes that would give characteristics like yield, disease resistance, drought tolerance and grain quality. Molecular markers are "flags" to particular genes. These markers help scientists identify whether a plant carries a desirable gene, even before the trait becomes visible.

So, it is possible to select at the seedling stage, which takes years of evaluation in the field.

Molecular Technique

1. Marker-Assisted Selection (MAS)

MAS uses DNA markers to spot plants carrying desired genes early in growth, skipping years of field waiting trial. In rice, breeders cross a high yield parent like Swarna with a donor carrying blast resistance (eg Pi54 gene) then test seedlings for markers linked to that gene.

Eg. Samba Mahsuri has xa13/xa21 genes for bacterial blight

2. QTL mapping and Gene pyramiding

Quantitative Trait Loci (QTL) mapping identifies chromosome regions controlling complex traits like drought tolerance (qDTY), grain size, using statistical links between markers and performance.

Gene pyramiding stacks multiple QTL/genes (eg. Sub1 for floods + Saltol for salinity) into one variety, creating "super rice" durable against multiple stresses—unlike single-gene failures.

Eg. CBMAS 14065 lines pyramid eight QTLs (qDTY1.1, Pi9, Gm4) for climate resilience, outperforming parents in multi-location trials.
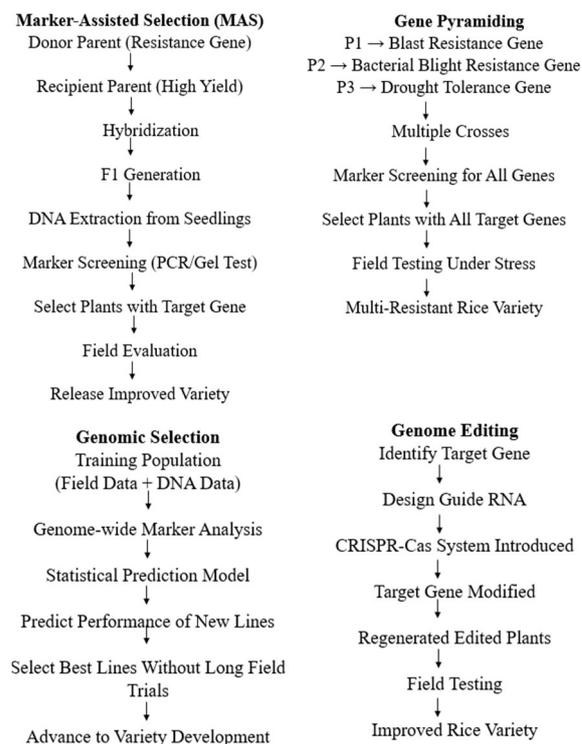
3. Genomic Selection (GS)

GS scans thousands of genome-wide markers to predict a plant's total breeding value, perfect for polygenic traits like yield where no single gene dominates. Models train on past data to rank seedlings without full phenotyping.

4. Genome Editing with CRISPR-Cas9

CRISPR acts as molecular scissors, precisely editing rice genes (eg. knocking out DEP1 for denser panicles) without foreign DNA, evading GMO labels.

Eg. India's DRR Rice 100 (Kamala) edits for early maturity variety.

Marker-Assisted Selection (MAS)
Donor Parent (Resistance Gene)
↓
Recipient Parent (High Yield)
↓
Hybridization
↓
F1 Generation
↓
DNA Extraction from Seedlings
↓
Marker Screening (PCR/Gel Test)
↓
Select Plants with Target Gene
↓
Field Evaluation
↓
Release Improved Variety

Gene Pyramiding
P1 → Blast Resistance Gene
P2 → Bacterial Blight Resistance Gene
P3 → Drought Tolerance Gene
↓
Multiple Crosses
↓
Marker Screening for All Genes
↓
Select Plants with All Target Genes
↓
Field Testing Under Stress
↓
Multi-Resistant Rice Variety

Genomic Selection
Training Population
(Field Data + DNA Data)
↓
Genome-wide Marker Analysis
↓
Statistical Prediction Model
↓
Predict Performance of New Lines
↓
Select Best Lines Without Long Field Trials
↓
Advance to Variety Development

Genome Editing
Identify Target Gene
↓
Design Guide RNA
↓
CRISPR-Cas System Introduced
↓
Target Gene Modified
↓
Regenerated Edited Plants
↓
Field Testing
↓
Improved Rice Variety

Improving Disease Resistance Through Molecular Breeding

Rice is affected by several destructive diseases, including:

- Blast disease
- Bacterial leaf blight

- Sheath blight

These diseases significantly reduce yield and increase pesticide dependency. The high-yielding varieties have been genetically enhanced through molecular breeding to produce specific genes of resistance. A technique known as gene pyramiding allows multiple resistance genes to be obliged delivery durable and broad-spectrum resistance. This reduces:

- Chemical pesticide usage
- Production cost
- Environmental pollution

Climate Change: Abiotic Stress Tolerance

Climate stress is a major threat to rice production which include:

- Drought
- Flooding (submergence)
- Salinity
- Heat

One remarkable achievement is the development of submergence-tolerant rice varieties using the Sub1 gene. Rice varieties carrying Sub1 can survive complete flooding for up to two weeks, providing relief to farmers in flood-prone areas. Similarly, molecular markers are used to improve drought and salinity tolerance, helping farmers adapt to climate change.

Grain Quality and Nutritional Enhancement

Grain and nutrients in rice are equally important in rice breeding. Molecular breeding has helped improve:

- Grain length and slenderness
- Cooking quality
- Aroma (especially in Basmati rice)
- Amylose content

Biofortification is another breakthrough. For example, Golden Rice has been developed to combat Vitamin A deficiency by enriching rice grains with beta-carotene. Similarly, zinc and iron-enriched rice varieties are being developed to fight hidden hunger.

Conclusion

The rice improvement process has shifted away from an observation based approach in the field to a precision, which is supported by the genome. Molecular breeding has transformed the conventional method of crop improvement to a faster, precise and science based approach. With the combination of the use of marker-assisted selection, genome selection, pest resistance, as well as grain quality, breeders can now develop rice varieties that adapt to high-yielding conditions, are resistant to stresses, are resistant to diseases, and are of high quality grain in a shorter period. Against the backdrop of climate change and increasing food demand, molecular breeding can be considered a viable solution as it can be used to create more rice with less water. It minimizes chemical inputs, increases the ability to withstand environmental pressures and promotes nutritional security by using biofortified varieties. Although infrastructure, cost and skilled manpower are some of the challenges facing biotechnology, it will still have more changes in the future with more investments made in the biotechnology and research. Finally, molecular breeding is not only a technological innovation, but a strategic tool to ensure food security in the whole world. The future of rice is the intelligent fusing of traditional knowledge and the power of advanced molecular tools- as rice ensures that the crop keeps on feeding the billions of people in the quickly changing world.