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Ramandeep Kaur
Ph.D. Scholar, Department of Horticulture, Faculty of Agriculture, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab, India

Sushil Kumar
Assistant Professor, Faculty of Agriculture, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab, India

Prabhjot Singh
Ph.D. Scholar, Department of Horticulture, Faculty of Agriculture, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab, India

Corresponding Author:
Sushil Kumar
Assistant Professor, Faculty of Agriculture, Guru Kashi University, Talwandi Sabo, Bathinda, Punjab, India

Marker-assisted breeding strategies for brinjal improvement: A review

Ramandeep Kaur, Sushil Kumar and Prabhjot Singh

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Abstract
Biotic and abiotic stresses like Fusarium wilt, shoot and fruit borer, drought, salinity and heat stress make it hard to develop better brinjal varieties. These stresses affect fruit yield and quality. Plant breeding helps improve crops by choosing genes. It takes a long time and is affected by the environment. This makes it hard to improve crops with traits. Marker-assisted breeding is a way to enable breeders to rapidly select. Also, introgress target genes or quantitative trait loci (QTLs) linked to desirable agronomic traits. Advances in marker technologies, such as simple sequence repeats (SSRs) and single nucleotide polymorphisms (SNPs), along with QTL mapping, genomics-assisted breeding, genome-wide association studies, and next-generation sequencing, increase breeding accuracy in brinjal. The review also discusses disease resistance, insect resistance and fruit quality. The review also discusses disease resistance, insect resistance and fruit quality. It talks about how to make brinjal strong against stress. There are challenges. Markers need to be checked. Some traits are hard to understand. There are not enough genomic resources. Future brinjal improvement programs will likely integrate marker-assisted breeding, genomic selection, CRISPR/Cas genome editing, phenomics, and artificial intelligence-based breeding.

Keywords: Eggplant, Marker-assisted breeding, Molecular markers, QTL mapping, Disease resistance, Genomics

Introduction

Eggplant (*Solanum melongena* L.), also known as brinjal or aubergine, is an important vegetable crop. It belongs to the Solanaceae family. Farmers grow it widely in subtropical areas of Asia, Africa, and the Mediterranean. [1, 2]. It is one of the vegetables in production and consumption after tomatoes, potatoes, and chilies. [3]. Eggplant can grow in different climates and can be grown year-round, which makes it very valuable [4]. Brinjal fruits are good for us because they have dietary fiber, carbohydrates, minerals, vitamins, and phytochemicals [5]. These things make brinjal a nutritious food. The fruits also contain phenols, flavonoids, anthocyanins, and chlorogenic acid, which help protect against diseases. [6]. Purple-colored brinjal varieties usually have more anthocyanin, which makes them more nutritious and better for us [7]. Brinjal is found in areas with different types [8, 9]. This genetic diversity gives breeders significant opportunities to develop varieties with improved yield, quality, and resistance [10]. Despite its agricultural and nutritional significance, various biotic and abiotic stressors constrain brinjal productivity. The shoot and fruit borer (*Leucinodes orbonalis*) causes substantial biotic stress. Bacterial wilt (*Ralstonia solanacearum*), Fusarium wilt, Verticillium wilt, and Phomopsis blight are the major diseases [12]. Drought, salinity, and elevated temperatures also present growing abiotic challenges, especially with climate change [13]. Breeders have used conventional techniques such as selection, hybridization, pedigree breeding, and backcross breeding to improve brinjal [14]. However, these methods take a lot of work and time, and they depend on the weather [15]. Polygenic inheritance and genotype-by-environment interactions complicate the selection of quantitative traits such as yield, fruit quality, and stress tolerance [16]. Marker-assisted breeding has therefore emerged as an efficient strategy to accelerate brinjal improvement [17]. We can breed plants by using special markers to look at the DNA. This helps us select the plants and speeds up the breeding process. Using these markers to help with breeding is becoming very important for making brinjal stronger against diseases, insects and bad weather and for making the fruit taste better [18]. Marker-assisted breeding is really good for this. It helps with disease resistance in brinjal insect resistance, in brinjal and making the fruit quality of brinjal better. [19].

2. Scenario of Brinjal Production

Farmers widely cultivate brinjal in tropical and subtropical regions [20]. Its significance is particularly notable in Asia, where favorable climatic conditions enable farmers to produce and consumers to eat brinjal year-round [21].

The FAOSTAT database says that farmers around the world produced about 59.31 million tons of eggplant in 2022. Then, eggplant production went up to about 60 million tons in 2023 [87]. China leads production, accounting for 64-65% of the global total. With an annual output of about 38-39 million tons [22]. India ranks second, producing 12.8-13.4 million tons. This is 21 to 22 percent of the world's total eggplant production. [24]. Egypt, Türkiye, Iran, and Indonesia also produce significant quantities [25]. In India, farmers grow brinjal on 0.73-0.78 million hectares, yielding 12.8-13.4 million tons annually [26]. Average productivity ranges from 18-20 t/ha but varies by region and cultivation system [26]. The principal brinjal-producing states are West Bengal, Odisha, Bihar, Gujarat, Maharashtra, Karnataka, and Andhra Pradesh. The main places where eggplant is grown in India are West Bengal, Odisha, Bihar, Gujarat, Maharashtra, Karnataka and Andhra Pradesh. [27]. West Bengal leads due to favorable agro-climatic conditions and extensive cultivation [27]. Indian farmers grow eggplant in fields and greenhouses. They use many methods to grow eggplant so that they can have it all year round [28]. Even though eggplant production is going up the amount of eggplant that farmers can get from their land is still not as high as it could be [29]. This is because of pests and diseases that can damage the eggplant [11]. Some pests like the shoot and fruit borers can cause a lot of damage to the eggplant. They can make the farmers lose 60 to 70 percent of their eggplant. Also, Bacterial wilt can cause a lot of damage to the eggplant. It can make farmers lose a lot of money in subtropical regions [30]. Climate change is also making it harder for farmers to grow eggplant. It is making it more likely that there will be droughts, much salt in the soil and too much heat. [13]. These are problems for farmers and they need to find ways to deal with them. This is why farmers and scientists are working together to develop types of eggplant that can grow well even with these problems. They are using technologies like marker-assisted breeding to develop these new types of eggplant. This technology can help them develop eggplant that's more resistant, to pests and diseases and can grow well in different conditions. [17, 18].

3. Concept and Principles of Marker-Assisted Breeding:

Breeders use a way of breeding called marker-assisted breeding. This is when they combine markers with the usual ways of breeding plants. Unlike the ways of DOIng things marker-assisted breeding does not just look at how the plants appear. [31, 32]. It looks at the DNA of the plants to see if they have the traits that are wanted. This breeding method is not affected by factors such as weather or soil. It makes the whole process of breeding plants more efficient. [33].

Marker-assisted breeding is really good for finding traits that are hard to see or take a long time to develop [34]. For example, some plants are resistant to diseases can handle tough weather. These traits can be hard to find phenotypically in the plants. With marker-assisted breeding, breeders can use DNA markers to find these traits. This makes it easier for breeders to pick the plants they want. Marker-assisted breeding is helpful for traits like disease resistance. How well plants can handle stress. It is also useful for things like the shape of the roots and the quality of the plants. Marker-assisted breeding is a help, to breeders because they can use it to select plants with the traits they want.[35].

Breeders typically use several approaches in marker-assisted breeding, including marker-assisted selection, marker-assisted backcross breeding, gene pyramiding, QTL mapping, and genomic selection [36]. These approaches have become more popular in brinjal breeding as pest and disease infestations and climate-related stress have made breeding increasingly challenging [37].

The efficiency of marker-assisted breeding depends heavily on the availability of high-quality molecular markers closely linked to target genes or QTLs [38]. Researchers have developed many different marker systems that have proved useful for brinjal improvement. These include SSR, SNP, RAPD, AFLP, and SCAR markers [39]. Currently, SSR and SNP markers remain the most popular because they offer repeatability, co-dominant inheritance, and high-throughput [40].

The best uses of marker-assisted breeding in brinjal have been making disease-resistant varieties of brinjal. Sülü *et al.* verified molecular markers associated with resistance to *Fusarium oxysporum*, *Verticillium dahliae*, and *Ralstonia solanacearum* in diverse eggplant breeding materials [41]. Their research demonstrates that marker-assisted selection significantly increases screening efficiency by enabling early detection of resistant genotypes.

The wild relatives of brinjal are very important because they have genes that help the plant fight off diseases and deal with stress. Tiwari *et al.* [42] highlighted the significance of pre-breeding and introgression of genes from wild plants such as *Solanum torvum*, *S. incanum,* and *S. insanum* for resistance to bacterial wilt and stress tolerance. Breeders have used marker-assisted introgression to successfully introduce desirable genes into cultivars. Overall, marker-assisted breeding has become a promising tool for accelerating genetic improvement in brinjal and will likely play a pivotal role in future breeding programs [43].

4. Molecular Markers Used in Brinjal Breeding

Breeders use molecular markers as vital tools in marker-assisted breeding because these genetic markers are associated with genes or regions of interest in the genome that determine important agronomic traits [44]. Over the years, researchers have developed and used several marker systems in brinjal breeding.

Researchers used Restriction Fragment Length Polymorphism (RFLP) as one of the early marker systems in crop breeding and genetics [45]. Although RFLP markers provide high reliability and reproducibility, their expensive and labour-intensive nature has prevented widespread application in marker-assisted breeding.

Researchers adopted Random Amplified Polymorphic DNA (RAPD) markers because the technique is simple, rapid, and relatively low in cost [46]. Researchers used RAPD markers extensively in early genetic diversity studies of brinjal, but their poor reproducibility has limited their application in advanced breeding.

Researchers found AFLP markers to be more polymorphic and reproducible than RAPD markers [47]. AFLP markers have proved highly useful for analyzing diversity and developing genetic linkage maps. Breeders now use SSR markers as the most widely used marker system in brinjal breeding because of their polymorphism, co-dominant inheritance, reproducibility, and even distribution across the genome [48]. SNPs represent the most modern and extensively used marker system in breeding [49]. Because plant genomes contain abundant SNPs and high-throughput genotyping technologies are available, breeders now consider SNP markers irreplaceable in genomics-assisted breeding. In addition, next-generation sequencing techniques have dramatically impacted marker development and genome-wide studies in brinjal [50]. As a result, high-density genetic maps and SNP genotyping give breeders unique opportunities for precise breeding.

Researchers conducting a new investigation used SSR markers in both cultivated and wild brinjal accessions and detected high levels of genetic variation, underscoring the importance of SSR markers for selecting diverse parental genotypes in breeding programs [51]. This result suggests that SSR markers remain highly useful for assessing genetic diversity and expanding the gene pool for breeding. Modern genomic studies show that SNP markers help identify specific genomic regions associated with fruit quality, yield, and disease resistance [50]. Increased SNP density mapping improves QTL detection and accelerates breeding.

5. Marker-Assisted Selection in Brinjal Improvement

Marker-assisted selection is really useful for breeding and it helps to make crop improvement faster. Breeders identify individuals with desirable genes using associated molecular markers rather than relying solely on phenotypic traits [52]. This technique proves particularly valuable in brinjal when the target trait is difficult to assess phenotypically, is strongly influenced by environmental factors, or appears only at later developmental stages [53]. Relevant traits include disease and stress resistance, biochemical composition, and root characteristics. One good thing about using markers to help with selection is that you can pick the ones early on. This is because these markers let breeders find the genes they want when the plants are still very young, like seedlings [54]. This means they can get rid of the ones early, which saves them money and helps them get more work done. In brinjal, breeders have widely used this method for disease resistance breeding, fruit quality improvement, and pest resistance [55]. Marker-assisted selection is really helpful for this reason. It makes marker-assisted selection more efficient.

Bacterial wilt (*Ralstonia solanacearum*) ranks among the major diseases affecting brinjal (Solanum melongena) cultivation in the tropics [56]. Researchers have made several efforts to identify molecular markers associated with bacterial wilt resistance. Developing molecular markers has allowed breeders to identify resistant genotypes without artificial inoculations, thereby improving the breeding process [41, 57].

The color of a fruit the shape of a fruit and the amount of anthocyanin in a fruit are really important when it comes to the quality of a brinjal [58]. By developing molecular markers for pigmentation genes, researchers have enabled breeders to select fruit phenotypes with enhanced nutritional value. Consequently, breeders now use marker-assisted selection as a critical tool to improve fruit quality.

6. Marker-Assisted Backcross Breeding in Brinjal Improvement

This method is faster and more precise than breeding because it uses molecular markers. Breeders like this method because it lets them combine traditional breeding methods with new technology [60]. Breeders use marker-assisted backcross breeding to introduce desired genes or quantitative trait loci (QTLs) into varieties while keeping the genetic makeup of the parent plant [31].

Usually, MABC breeding has three parts: foreground selection, recombinant selection, and background selection [32]. Breeders use molecular markers for foreground selection to detect plants that carry the required gene or QTL. For recombinant selection, breeders aim to reduce linkage drag by limiting the transmission of unwanted donor chromosomal regions around the target locus. For background selection, breeders quickly restore the recurrent parent's genome, thereby reducing the breeding period [33]. Brinjal (eggplant) has become increasingly popular for MABC breeding as breeders use it to introduce resistance genes from wild relatives into cultivated varieties. Wild species, including *Solanum torvum, S. insanum, S. incanum*, and *S. aethiopicum*, harbor useful genes that confer disease resistance and abiotic stress tolerance [42].

Marker-assisted backcross breeding (MABB) remains an important approach in brinjal genetics because it enables breeders to introgress resistance to bacterial wilt into susceptible but productive brinjal varieties from resistant donor varieties. Researchers conducted studies on recombinant inbred populations derived from crossing the resistant genotype AG91-25 with susceptible genotypes and identified important resistance genes linked to bacterial wilt resistance [61]. Using the MABB technique, breeders effectively introgressed the resistance genes into susceptible genotypes without compromising fruit quality or agronomic performance. Salgon *et al.* emphasized the importance of the major resistance gene ERs1 located on chromosome 9 in conferring resistance to various *Ralstonia solanacearum* strains [62].

Wild species such as *Solanum torvum* and *Solanum sisymbriifolium* display significant resistance against bacterial wilt and soil-borne diseases [63]. Breeders have used marker-assisted backcross breeding with these wild donors as an effective way to broaden the brinjal gene pool and improve its resilience in stressful environments. Breeders will continue to hasten the introgression of traits in brinjals by using marker-assisted backcross breeding, high-density molecular markers, and next-generation sequencing technologies.

7. QTL Mapping and Trait Identification in Brinjal

Breeders use quantitative trait loci (QTL) mapping as an effective method to detect genomic regions associated with quantitative traits, such as yield, fruit quality, disease resistance, and abiotic stress tolerance [64]. Many economically important traits in brinjal are governed by multiple genes and influenced by environmental factors, so breeders consider QTL mapping an essential tool in modern breeding programs [65].

QTL mapping ns between phenotypic variability and molecular markers on the genome [66]. Breeders commonly use F2, recombinant, such as doubled haploids, and backcross populations [67]. Researchers have identified QTLs for various economically important traits, including fruit length, diameter, weight, shape, anthocyanin content, flowering time, and disease resistance [68].

Researchers achieved one of the first successful applications of QTL mapping in brinjal by studying fruit morphology. They mapped several QTLs for fruit morphology traits, such as shape, size, and weight. Researchers found a substantial number of QTLs for fruit length, width, and weight, distributed across different chromosomes [69]. These QTLs explain significant amounts of phenotypic variation and serve as valuable tools for selecting market-desirable fruits. The development of new SNP-based genetic maps has improved QTL resolution and facilitated further identification of genomic regions responsible for fruit quality-related traits [50].

Bacterial wilt poses one of the greatest threats in regions where growers cultivate brinjal [56]. Contemporary QTL mapping studies have identified relatively stable genomic regions associated with resistance to bacterial wilt. In studies by Xiao *et al., researchers localized* the major QTLs associated with bacterial wilt resistance on chromosome 4 in eggplant [70]. Researchers have also identified some candidate genes involved in the mechanisms of bacterial wilt resistance. These findings indicate significant potential for marker-assisted breeding. Earlier studies identified stable QTLs on chromosomes 3, 6, and 9 that determine plant resistance to different *Ralstonia solanacearum* strains [62]. This discovery is especially important for breeding varieties with high stability against pathogen populations.

Recent studies have shown data that certain QTLs in brinjal affect rhizosphere microbial recruitment and subsequent suppression of bacterial wilt [71]. This emerging research direction offers promising opportunities for integrating host-genome information into microbiome-assisted breeding.

8. Disease Resistance Breeding in Brinjal

Breeders consider disease resistance breeding a key application of MAS in brinjal. Bacterial wilt, Fusarium wilt, Verticillium wilt, little leaf, and Phomopsis blight are among the main diseases of brinjal that may reduce yield and quality. Traditional breeding methods for disease-resistant crops have significant drawbacks. One issue is that the environment can be really different from one place to another. However, marker-assisted breeding offers more efficiency and accuracy than conventional breeding because it enables breeders to identify resistant genotypes early. Bacterial wilt (caused by *Ralstonia solanacearum*) is one of the most devastating diseases in tropical and subtropical climates, causing yield losses of 11% to 96% depending on the genotype, pathogen, and environment.

Researchers have demonstrated success in identifying disease resistance in cultivated brinjal and its wild relatives through several experiments. For instance, plants of the Solanum torvum, Solanum incanum, and *Solanum sisymbriifolium* species exhibit high resistance to bacterial wilt, highlighting their significance in breeding brinjal. Researchers have identified various marker types for bacterial wilt disease, including SSR, AFLP, and SNP markers. The ERs1 locus is one of the most important genomic regions associated with breeding for disease resistance.

Fusarium wilt of brinjal, caused by *Fusarium oxysporum*, has greatly limited brinjal productivity in many production areas. Marker-assisted selection has improved resistance identification by enabling breeders to test breeding material faster and more accurately. Sülü *et al.* confirmed the usefulness of markers associated with Fusarium wilt resistance [41].

Little leaf disease, caused by phytoplasma, also plays a major role in brinjal production. Recent studies have highlighted the usefulness of SSR markers in mapping populations developed for resistance to little leaf disease [42]. Marker-assisted breeding offers promising prospects for developing brinjals resistant to this emerging pest. Breeders will likely rely increasingly on marker-assisted resistance breeding in light of climate change.

9. Insect Resistance Breeding in Brinjal

Insect pests pose major biological constraints on the growth and yield of brinjal (*Solanum melongena*) worldwide [77]. Of these, the shoot and fruit borer (*Leucinodes orbonalis Guenée*) remains one of the most devastating insect pests, still presenting a serious challenge to commercial brinjal cultivation [11]. This pest bores into young shoots during vegetative growth and into fruits during the reproductive period, causing tremendous damage, significant yield losses, and poor quality [78]. Severe infestations can cause yield losses of 60% to 70%, and sometimes even higher than 80% [29]. Farmers depended on multiple insecticide sprays to combat this pest. which increases production costs and raises concerns about pesticide residues and the environment [79]. These challenges further highlight the need for breeders to develop brinjal varieties resistant to insect pests using genetic improvement techniques. Breeding for insect resistance remains difficult due to the polygenic inheritance of resistance and its environmental interactions [80].

Researchers have conducted several studies to find sources of resistance and respective markers for shoot and fruit borer resistance in brinjal. Wild relative plants, such as *Solanum sisymbriifolium*, *S. torvum*, and *S. incanum*, have proved useful in this regard [81]. Researchers have correlated molecular markers for biochemical defense mechanisms, including phenolic and glycoalkaloid compounds, with lower pest attacks. Modern genomic analysis shows that pest resistance in brinjal involves multiple defense mechanisms, including secondary metabolism, trichomes, and fruit chemical composition [82].

Bt brinjal, which contains the Cry1Ac gene providing resistance against shoot and fruit borer, is one of the most common examples of insect-resistant breeding in brinjal [83]. Field trials have demonstrated a significant decrease in pest infestations and pesticide use. While regulation varies from country to country, breeders continue to use Bt brinjal as an important example of insect resistance breeding with molecular techniques [84]. Marker-assisted breeding, together with genomic techniques, allows breeders to develop insect-resistant varieties without transgenes.

10. Fruit Quality Improvement in Brinjal

Fruit quality remains a major breeding target in brinjal because it influences consumer preference, economic value, and processability [85]. Breeders focus on fruit shape, size, color, texture, storage life, taste, and nutritive value as important fruit quality characters. Brinjal displays considerable variability in fruit shape, ranging from spherical to cylindrical, and in fruit color, including white, green, striped, and deep purple varieties [9]. These traits highlight the importance of fruit quality improvement as a breeding target in brinjal. Consumer interest in functional foods and health-enhancing vegetables has increased, making nutritional quality another major criterion for brinjal breeding [86]. Brinjal fruits provide phytochemicals such as anthocyanins, chlorogenic acid, phenols, and flavonoids, which give brinjal its antioxidant activity and beneficial health effects [6]. Breeders have found marker-assisted selection especially helpful for identifying genomic loci associated with fruit quality traits. Researchers have identified several quantitative trait loci (QTLs) for fruit shape, fruit weight, fruit color, anthocyanin accumulation, and biochemical composition [68].

Fruit morphology remains one of the most important market-preferred characteristics of *Solanum melongena*. Researchers have identified significant QTLs for fruit shape, length, and weight in several studies [69]. These QTLs contribute to substantial phenotypic variation and help breeders use marker-assisted selection for market-preferred fruit phenotypes. The development of high-density SNP mapping technology now allows researchers to more accurately localize QTLs controlling fruit morphology characteristics [50].

Anthocyanin content determines the pigmentation and nutritional quality of *Solanum melongena* fruits [87]. Purple brinjal genotypes typically contain higher levels of anthocyanins and exhibit greater antioxidant activity. Recent molecular analyses have enabled researchers to identify the key genes of the anthocyanin pathway, including regulatory genes involved in the pigment network [81]. Breeders have increased breeding efficiency by using marker-assisted selection for these genes.

11. Abiotic Stress Tolerance in Brinjal

Abiotic stresses such as drought, salinity, and heat increasingly threaten vegetable crops under climate change [13]. Although brinjal tolerates different stresses, it cannot withstand severe environmental stresses during flowering and fruiting [51]. Drought stress reduces plant growth, flowering, fruiting, and yield. Salinity stress impairs nutrient absorption, osmosis, and plant physiology [56]. Heat stress lowers pollen fertility and reduces productivity [60]. Breeders face significant challenges in breeding for abiotic stress tolerance, as these traits are complex and controlled by multiple genes [69]. Marker-assisted breeding offers several advantages for selecting stress-resistant genotypes.

Researchers have recently identified genomic regions responsible for drought resistance in brinjal and other Solanum species [40]. Root architecture, stomatal conductance, and osmotic adjustment play important roles in drought resistance. Breeders now widely use wild Solanum species, such as *S. insanum* and *S. incanum, because they* harbor valuable alleles for drought resistance [42].

Salinity limits production in irrigated farming. Researchers have shown that marker-assisted selection can increase salinity tolerance by introducing tolerance-related genomic segments from wild germplasm [47]. Current research demonstrates that breeders can achieve tolerance through several mechanisms, including maintaining proper ion balance, osmoregulation, and stress-induced gene expression [48]. Breeding for tolerance to abiotic stress remains one of the most promising areas in marker-assisted breeding of brinjal.

12. Challenges in Marker-Assisted Breeding of Brinjal

Brinjal improvement is still a job, even though we have made good progress in marker-assisted breeding. There are a few problems that stop us from using this method more widely. The lack of reliable trait-specific markers for key agronomic traits remains a major limitation. We do not have markers for important traits, such as yield or fruit quality. Things like yield and fruit quality are hard to pass on because they are influenced by factors and the environment has a big say in them. High genotyping costs and insufficient infrastructure for molecular breeding further restrict adoption, particularly in developing countries. Additionally, the narrow genetic diversity of brinjal crops limits the availability of desirable alleles for trait improvement.

13. Future Prospects

Future directions in brinjal (or eggplant) breeding involve combining marker-based and genomic techniques such as GWAS, genomic selection, speed breeding, and CRISPR/Cas genome editing [80]. Researchers can use GWAS to map marker-trait associations at high resolution in different germplasms [102]. Genomic selection allows breeders to improve several traits of interest simultaneously using whole-genome marker data [83]. Genome-editing tools such as CRISPR/Cas enable precision engineering of genes responsible for yield, quality, and stress tolerance [84]. These advances in technology will likely revolutionize brinjal breeding. The convergence of phenomics, bioinformatics, artificial intelligence, and genomics-assisted breeding will also accelerate the breeding of improved brinjal cultivars [87].

Table 1: Major molecular markers used in brinjal breeding [37, 50]

RFLP	DNA polymorphism via restriction enzymes	Early genome mapping, diversity analysis	Highly reliable	Labor-intensive, costly
RAPD	Random DNA amplification	Genetic diversity studies	Simple, low cost	Poor reproducibility
AFLP	Selective PCR amplification	Diversity studies, linkage mapping	High polymorphism	Complex protocol
SSR	Repeated DNA motifs	MAS, QTL mapping, diversity studies	Co-dominant, highly polymorphic	Moderate cost
SNP	Single nucleotide variation	Genomic selection, precision breeding	High-throughput, highly abundant	Requires advanced facilities
SCAR	Sequence-characterized amplified region	Trait-specific marker selection	Highly specific	Limited marker availability

Source: Compiled from published literature [37, 50]

Table 2: Important QTLs identified in brinjal for major traits [61, 71]

Fruit length	Chr 2, 3	Controls elongated fruit phenotype	Fruit shape breeding
Fruit diameter	Chr 5	Controls fruit width variation	Market-preferred fruit type
Fruit weight	Chr 3, 5	Major determinant of yield	Yield improvement
Anthocyanin content	Chr 10	Regulates fruit pigmentation	Nutritional quality
Bacterial wilt resistance	Chr 4, 9	Major resistance loci identified	Disease resistance breeding
Flowering time	Chr 1, 6	Controls earliness	Early cultivar development
Drought tolerance	Multiple loci	Root and stress-response traits	Climate resilience

Source: Compiled from QTL mapping studies [61, 71]

Table 3: Major diseases/insect pests and linked markers in brinjal [72, 87]

Bacterial wilt	*Ralstonia solanacearum*	11-96%	Well studied
Fusarium wilt	*Fusarium oxysporum*	Moderate to severe	Validated markers available
Verticillium wilt	*Verticillium dahliae*	Moderate	Limited marker studies
Phomopsis blight	*Phomopsis vexans*	Severe	Emerging marker studies
Little leaf disease	Phytoplasma	Moderate	SSR mapping available
Shoot and fruit borer	*Leucinodes orbonalis*	60-70%	Limited markers

Source: Compiled from disease and insect resistance studies [72, 87]

14. Conclusion

Breeders have adopted marker-assisted breeding as a principal strategy to rapidly improve brinjal. People working in breeding have made improvements in a few areas. They have made progress in growing plants that can fight off diseases, insects, and other things that affect them. They have also made fruits taste better and made plants stronger so they can handle conditions. Integrating marker technologies, quantitative trait loci (QTL) analysis, and genomics-based approaches has substantially increased breeding efficiency and precision. There are still some problems with growing brinjal, like it is hard to find markers, it is tough to figure out how some traits are passed on and it costs a lot to do the genetic testing. Recent developments in genomics and molecular breeding will likely transform brinjal improvement strategies. Breeders will need to integrate conventional breeding with marker-assisted breeding, genomic selection, and genome editing as central components of future brinjal breeding initiatives.

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