4.4 Resistance gene pyramiding

Resistance gene pyramiding combines multiple resistance genes and/or QTLs into a single variety to achieve broader and more durable resistance. Through marker-assisted pyramiding, genes such as Ty-1, Ty-2, and Ty-3 for tomato yellow leaf curl disease, Ph-2 and Ph-3 for late blight, and the Mi gene for root-knot nematode resistance have been integrated into the same genetic background. This has resulted in lines and hybrids with high overall resistance and stable yield under disease pressure (Prabhandakavi et al., 2021).

Double PCR and linked marker techniques allow efficient stacking of resistance genes for viruses and soil-borne diseases through backcrossing, enabling predictable recovery of elite genetic backgrounds with fewer plants.

Gene editing further expands the ability of gene pyramiding. Using multiplex CRISPR/Cas systems, multiple S or R genes can be edited at the same time, producing broad-spectrum resistance in a single generation and avoiding linkage drag (Tiwari et al., 2023). Combining resistance genes with different mechanisms and integrating good agronomic management practices is key to achieving long-term stable resistance in high-quality tomato varieties.

5 Disease-Resistant Varieties and Their Performance

5.1 Commercialized disease-resistant varieties

Widely used cultivars and hybrids usually carry resistance to key diseases such as Fusarium wilt, Tomato yellow leaf curl disease (TYLCD), Tomato spotted wilt virus (TSWV), and bacterial wilt. These resistances may exist individually or be combined through gene pyramiding. In Mexico, commercial Saladette-type hybrids carrying resistance genes to Fol races 1-3, TYLCV, and TSWV not only meet strict quality standards in both the United States and domestic markets, but also show early maturity (Lafrance et al., 2024). In India and other regions, F1 hybrids with resistance to multiple diseases (such as early blight, bacterial wilt, and leaf curl disease) have been widely used for both fresh consumption and processing purposes (Kaushal et al., 2020).

5.2 Yield stability and adaptability

The performance of disease-resistant varieties is influenced by season, production system, and disease pressure. In Mali, AVTO1710 can still maintain a relatively high yield (40.9 t/ha) during the rainy season, when many local varieties perform poorly, while VIO43614 performs best under drier conditions with high TYLCD incidence, showing good adaptability to different environments (Bihon et al., 2022). In Honduras, the line AVTO1903 shows high marketable yield under both open-field (101.3 t/ha) and greenhouse conditions (62.1 t/ha), indicating stable performance across cultivation systems (Flores et al., 2024). Late blight-resistant varieties such as “Mountain Gem” also show yield differences across regions, with clear yield improvement under grafting conditions, highlighting the importance of multi-location trials for resistant materials (Reeves et al., 2023).

5.3 Quality traits of disease-resistant varieties

Studies show that disease resistance can be combined with good fruit quality. In the Sinaloa region, hybrids resistant to Fol, TYLCV, and TSWV usually meet international standards in fruit firmness, color, pH, total soluble solids (TSS), acidity, and TSS/acid ratio, and some of them also have early maturity and good market quality (Lafrance et al., 2024). Differences exist among resistant materials in traits such as firmness, TSS, pH, dry matter content, and fruit shape index, allowing breeders to select lines that match local consumer preferences. Research on late blight-resistant families shows that strongly resistant genotypes can also approach the ideal type (ideotype), with good performance in fruit size, color, firmness, acidity, and soluble solids content (Copati et al., 2024). In addition, phenotypic analysis of diverse germplasm indicates that some resistant lines are not only high-yielding, but also have higher vitamin C content, antioxidant activity, and polyphenol levels, suggesting good potential for breeding varieties with both disease resistance and enhanced nutritional quality (Grozeva et al., 2020).

6 Integration of Disease Resistance and High-Quality Production

6.1 Balance between resistance and fruit quality

Breeding studies show that disease resistance and quality can be improved together, but there is still a certain trade-off between them. Materials carrying multiple Ty genes to enhance resistance to TYLCV usually show strong resistance. However, when selecting for low disease index and high yield, they are often accompanied by a