al., 2019a). Under these climatic conditions, radish is commonly rotated with crops such as cabbage, tomato, or potato, forming intensive vegetable production systems. Winter production takes advantage of the long frost-free period, but growers must also deal with challenges such as high rainfall and soil acidification.

7.3 Farmer adoption and local adaptation strategies

In the major radish-growing regions of China, farmers often adjust sowing dates, planting density, and fertilization programs according to local temperature conditions and soil characteristics to improve production efficiency. Studies on off-season radish production in Nepal using insect-proof net houses or shading facilities showed that farmers commonly achieve off-season production by shifting sowing dates to late winter or early spring, using shading structures to reduce heat and strong light stress, and selecting hybrid varieties that can maintain stable fleshy root development under unsuitable temperature conditions. In China, the promotion of improved hybrid varieties, optimization of plant spacing, adoption of drip irrigation, and implementation of integrated nutrient management have become important technical approaches for maintaining uniform root size and reducing physiological disorders during cool-season production.

7.4 Yield and economic benefit analysis

Data from large-scale multi-location experiments showed that, under suitable climatic conditions and optimized water and fertilizer management, the economic yield of radish in China can reach 30~33 $t \cdot ha^{-1}$ or even higher. A significant positive relationship has been found between yield and the balanced uptake of nitrogen, phosphorus, and potassium nutrients (Sharma et al., 2025). Economic analyses of nutrient management and irrigation strategies indicated that optimized fertilization programs and drip irrigation systems can significantly increase net returns and benefit–cost ratios compared with traditional farmer practices. The main reasons are higher yields and improved efficiency in the use of production inputs.

8 Future Prospects and Research Directions

8.1 Integration of genomics and precision breeding

The availability of high-quality, chromosome-level radish genomes, together with abundant SNP (single nucleotide polymorphism) and SV (structural variation) marker resources, has provided a strong foundation for genome-assisted breeding. Genome-wide association studies (GWAS) and transcriptome analyses have identified several important regulators involved in low-temperature response and plant growth, including the RsWRKY40-RsSPS1-CBF regulatory module, RsERF40, RsWRKY49, and RsCDF3 (Xu et al., 2023b). These findings provide technical support for precise molecular marker-assisted selection (MAS), genomic selection (GS), and speed breeding aimed at improving complex traits such as cold tolerance, late bolting, and yield.

8.2 Breeding climate-adapted radish varieties

Climate change is expected to alter temperature and precipitation patterns, which will further affect the geographic distribution of both wild and cultivated radish populations. Wild radish and diverse cultivated germplasm contain a large number of stress-resistant alleles that can be used to improve resistance to various biotic and abiotic stresses (Han et al., 2023). By combining these genetic resources with knowledge of low-temperature response regulatory networks, including regulators such as RsWRKY40, RsERF40, and RsWRKY49, it will be possible to develop new winter radish varieties with multiple stress-resistance traits, including tolerance to cold, drought, and heat. Such varieties will be better suited to future climate conditions that are expected to become more complex and variable.

8.3 Development of smart agriculture and digital cultivation technologies

Internet of Things (IoT)-based environmental monitoring systems and smart greenhouse technologies have shown clear advantages in radish production. Compared with conventional cultivation methods, these technologies have achieved better performance in seed germination, plant growth, and resource-use efficiency, demonstrating the value of sensor-based management systems (Lafta and Abdullah, 2024). In the future, the integration of sensor networks, automated control systems, artificial intelligence (AI), and big data analytics will further improve irrigation management, temperature regulation, and nutrient supply. These technologies can also provide accurate decision-making support for winter radish production in greenhouses and protected cultivation systems.