

Case study

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Cold-Resistant Radish Varieties for Winter Production in Southern China

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Abstract With the development of the winter vegetable industry in southern China, climatic factors such as low temperature, cold waves, and frost have become major environmental stresses limiting stable and high-yield radish production. This study focuses on the winter agricultural climate characteristics of southern China and their effects on radish cultivation. It explains the morphological, physiological, and molecular biological basis of cold tolerance in radish and summarizes the mechanisms of osmotic adjustment, antioxidant defense systems, plant hormone regulation, and low-temperature-responsive gene networks involved in cold tolerance formation. At the same time, the study reviews the diversity of radish germplasm resources in China, local cold-tolerant varieties, advances in conventional breeding techniques, and progress in molecular breeding research. The advantages of representative cold-tolerant varieties in terms of yield, quality, and environmental adaptability are also analyzed. Combined with key cultivation practices, including optimization of sowing time, water and fertilizer management, protected cultivation, and integrated pest and disease control, this paper discusses efficient winter radish production systems and typical regional application cases. The coordinated application of cold-tolerant variety breeding and regional cultivation technologies is an important approach to improving the stability and economic benefits of winter radish production in southern China. In the future, greater efforts should be made to integrate genomics with precision breeding technologies, improve cold-tolerance evaluation systems, and promote the application of smart agriculture technologies, providing both theoretical support and technical guidance for the development of efficient, environmentally friendly, and sustainable winter vegetable production systems.

Keywords Radish (*Raphanus sativus* L.); Cold tolerance; Winter production; Germplasm resources; Molecular breeding; Cultivation technology; Southern China

1 Introduction

Winter vegetable production is an important part of the year-round vegetable supply system in China. In regions with suitable accumulated temperature conditions, off-season production can be achieved, creating strong market competitiveness. Southern China is one of the major winter-spring vegetable production regions and has comparative advantages for winter vegetable cultivation because of its favorable climate and resource conditions. However, it still faces the challenge of low-temperature weather events, which can reduce yield stability and product quality (Hou and Wang, 2024). Under these circumstances, improving the adaptability and stress resistance of major winter crops is of great importance for ensuring regional food security and promoting sustainable and intensive agricultural development.

Radish (*Raphanus sativus* L.) is one of the most important root vegetables in China and worldwide. It is widely cultivated across different climate zones and growing seasons. In China alone, the planting area of radish reached approximately 1.2 million hectares in 2016, with a fleshy root production of 44.6 million tons, accounting for about 40%~47% of the global planting area and production of radish (Kurina et al., 2021). According to different planting seasons, radish can be classified into spring radish, summer radish, autumn radish, and winter radish. Among them, autumn and winter radishes are dominant in many regions, accounting for approximately 20%-50% of the total autumn vegetable planting area (Zhang et al., 2019a). Because of its short growth cycle, diverse root shapes and colors, and high nutritional value, radish has become a key crop in intensive vegetable production systems and an important source of income for many small-scale farmers.

Although radish has relatively strong environmental adaptability, it is essentially a cool-season crop. Its growth process, especially the fleshy root development stage, is highly sensitive to temperature changes. It is generally accepted that the highest fleshy root yield can be achieved when day/night temperatures are maintained within the range of 19/13 °C ~24/18 °C. Both excessively high and excessively low temperatures can negatively affect fleshy root development and quality (Khan et al., 2022; Oh et al., 2022). Under low-temperature stress, secondary growth of the fleshy root, cambial activity, and root enlargement are significantly inhibited, resulting in reduced yield and deteriorated quality. Low temperatures can also damage cell membrane structures, disrupt the homeostasis of reactive oxygen species (ROS), and slow seed germination and early seedling growth, thereby reducing seedling establishment rates in winter crops. These constraints are particularly serious in open-field winter production systems in southern China, where periodic cold waves often cause substantial economic losses to farmers.

Therefore, breeding and selecting cold-tolerant radish varieties has become an important strategy for stabilizing winter radish production. At the molecular level, several transcription factors involved in low-temperature stress responses, including members of the ERF, WRKY, MYB, and CDF families, such as RsERF40, RsWRKY49, RsMYB90, and RsCDF3, have been shown to enhance cold tolerance by regulating the expression of cold-responsive (COR) genes, osmotic adjustment, cell wall reinforcement, ROS balance, and root growth under low-temperature conditions. At the population level, radish exhibits extensive genetic diversity in morphological traits, growth characteristics, and biochemical properties, with significant differences among ecological types and geographical populations.

Based on this background, the present study focuses on cold-tolerant radish varieties suitable for winter production in southern China. The objectives of this study are: (i) to explain the important role of radish in winter vegetable production systems in relation to the needs of winter vegetable cultivation in southern China; (ii) to systematically summarize the physiological and molecular mechanisms through which low-temperature stress restricts radish growth and fleshy root development; (iii) to analyze genetic diversity resources and breeding approaches related to cold tolerance and winter adaptability; and (iv) to provide theoretical support and practical references for the breeding, selection, and regional promotion of radish varieties with strong cold tolerance, thereby achieving stable yield, high productivity, and improved quality in winter radish production.

2 Agricultural Climate Characteristics of Winter in Southern China

2.1 Temperature variation patterns and occurrence of low-temperature stress

Southern China is generally characterized by a mild and humid winter climate. In southeastern China, the average daily temperature during winter is usually maintained at around 7 °C~8 °C, while the annual mean temperature in many areas ranges from 14 °C to 18 °C. The frost-free period can exceed 230~340 days (Freychet et al., 2021). Historical climate reconstruction studies have shown that although a clear long-term warming trend has occurred, especially with a rapid increase in winter temperatures since the late twentieth century, winter temperatures in southern China still exhibit considerable year-to-year variability (Fu and Ding, 2021). Under the background of global warming, extreme cold events have not disappeared but instead show clear interdecadal fluctuations. In recent decades, some regions of China have even experienced an increase in regional extreme cold events. Analyses of frost days across the country indicate that although the overall frost-free period has become longer and the number of frost days has decreased, frost and cold-wave events still occur periodically in southern China, posing potential risks to crops that are sensitive to low temperatures.

2.2 Regional differences (e.g., the Yangtze River Basin and South China subtropical regions)

There are significant agroclimatic differences between the Yangtze River Basin (YZRB) and the more southern subtropical regions. The Yangtze River Basin has a typical subtropical monsoon climate, characterized by mild and rainy winters and a frost-free period of approximately 230~326 days. However, the region is also known for frequent late-spring cold events and relatively high climate risks during the transition from winter to spring (Lei et al., 2024). In contrast, South China, including provinces such as Guangdong, Guangxi, and Hainan, has a warmer climate and a longer frost-free period. Even during the coldest month, temperatures generally remain above 1 °C (Yu et al., 2022).

Even within the Yangtze River Basin, substantial differences exist among the upper, middle, and lower reaches in terms of average temperature, precipitation, and sunshine duration. These variations result in different cropping systems and different levels of sensitivity to climate anomalies (Xu et al., 2019). Such regional climatic differences directly affect the suitable sowing windows for winter vegetables and the level of climate-related risks they face.

2.3 Effects of cold waves and frost events on vegetable crops

Although winters in southern China are generally mild, cold waves and large-scale persistent extreme low-temperature events can still cause sudden temperature drops, freezing rain, and prolonged cold conditions, thereby affecting agricultural production in southern and southeastern China. For example, the severe cold-wave events that occurred during the winters of 2008 and 2016 brought historically low temperatures and freezing rain, causing not only transportation disruptions and infrastructure damage but also serious impacts on agricultural production (Liao et al., 2020).

At the national scale, winter low-temperature events vary considerably in both frequency and intensity. Strong cold-wave events in southern China generally last longer than those in northern China, and December is the period with the highest occurrence frequency and the longest duration of cold waves (Chen et al., 2022). When extreme low temperatures occur during critical growth stages, they can significantly reduce the yields of overwintering crops such as winter wheat and rapeseed, with the degree of impact varying among regions (Xiao et al., 2018; Huang et al., 2020; Zhao et al., 2024). In the double-cropping systems of the Yangtze-Huaihe Plain, extreme weather events occurring during sowing or seedling establishment of winter crops can suppress vegetation growth throughout the growing season and ultimately reduce crop yield formation (Chen et al., 2024).

3 Physiological and Molecular Basis of Cold Tolerance in Radish

3.1 Morphological traits associated with cold tolerance

Compared with cold-sensitive materials, cold-tolerant radish genotypes can better maintain secondary growth of the fleshy root, cambial activity, and root meristem size under low-temperature conditions. Overexpression of RsERF40 and RsWRKY49 promotes elongation and radial expansion of fleshy roots or hairy roots, indicating that these genes enhance cell expansion and cell division under cold stress. RsERF40 strengthens cell wall structure by upregulating the expression of cell wall-related genes (RsCESA6 and RsEXPB3), thereby maintaining root tissue stability under low-temperature conditions. Similarly, RsWRKY49 increases root meristem size and promotes cell division, allowing roots to maintain continuous growth in cold environments.

3.2 Physiological responses (osmotic regulation and antioxidant activity)

Cold-tolerant plants usually accumulate osmotic adjustment substances such as soluble sugars and proline to stabilize cell membrane structure and maintain cellular osmotic potential. In radish, sucrose synthesized by RsSPS1 is an important osmotic regulator. Higher sucrose levels help maintain cambial activity and improve cold tolerance, whereas silencing RsSPS1 results in reduced sucrose, proline, and chlorophyll contents, while increasing the accumulation of membrane damage indicators, including malondialdehyde (MDA) and hydrogen peroxide (H₂O₂) (Chen et al., 2025b). RsERF40 enhances osmotic regulation by activating COR genes and promoting the accumulation of cryoprotectants.

Maintaining reactive oxygen species (ROS) homeostasis is another key physiological mechanism for plant adaptation to cold stress. Low temperatures often cause excessive ROS accumulation, making an efficient antioxidant system essential. Overexpression of RsERF40, RsCDF3, and RsSHRc reduces ROS and MDA accumulation while increasing proline content and overall antioxidant capacity, thereby alleviating oxidative damage. Among them, RsCDF3 directly represses the expression of the NADPH oxidase genes RsRbohA and RsRbohC, reducing ROS production and establishing a positive feedback mechanism that favors ROS homeostasis (He et al., 2023). These findings are consistent with studies in other crops, where increased activities of superoxide dismutase (SOD), peroxidase (POD), and catalase (CAT), together with higher levels of flavonoids and ascorbic acid, are generally associated with stronger cold tolerance (Raza et al., 2021; Liu et al., 2022; Xu et al., 2023a).

3.3 Role of plant hormones in low-temperature adaptation

Plant hormone signaling is closely linked to cold-stress responses. Cross-species studies have shown that abscisic acid (ABA), auxin, gibberellins, jasmonic acid, salicylic acid, ethylene, brassinosteroids, and cytokinins all participate in plant cold acclimation by regulating gene expression, growth and development, and ROS signaling pathways.

In radish, the ethylene-responsive factor RsERF40 clearly illustrates the integration of hormone signaling and cold signaling. As a member of the AP2/ERF transcription factor family, RsERF40 not only functions in ethylene-related signaling pathways but also regulates cold-induced COR genes and cell wall remodeling processes (Zhou et al., 2025). In addition, transcription factors from the WRKY and MYB families are often regulated by hormonal signals and contribute to balancing plant growth and defense responses under low-temperature conditions (Feng et al., 2025; Qin et al., 2026). Although studies on hormone profile changes in radish under cold stress remain limited, hormone-regulated transcription factors are considered key regulatory nodes linking hormone signaling, ROS homeostasis, and sustained growth.

3.4 Key genes and molecular regulatory pathways associated with cold tolerance

Cold tolerance in radish is regulated by both CBF-dependent and CBF-independent pathways. RsWRKY40 activates RsCBF1 and RsCBF2, while also enhancing RsSPS1 expression, forming a transcriptional regulatory module that links sucrose accumulation with the classical CBF-COR signaling cascade. Similarly, RsWRKY49 transcriptionally activates RsCBF2 and RsNR2, and variations within its promoter region are associated with differences in cold tolerance among genotypes (Chen et al., 2025a).

RsERF40 represents a CBF-independent cold-tolerance pathway. This gene directly upregulates the expression of RsCOR78, RsCOR413PM1, and several cell wall-related genes, thereby promoting cryoprotectant accumulation, maintaining osmotic stability, and supporting fleshy root growth. RsMYB90 binds to the promoter of RsCOR78 and activates RsUFGT expression, enhancing anthocyanin biosynthesis and improving ROS scavenging capacity under low-temperature conditions (Li et al., 2025).

In addition to transcription factors, the GRAS family member RsSHRc is also an important regulator of cold tolerance. Its expression is induced by low temperatures, promoting ROS scavenging, reducing MDA accumulation, and increasing proline content. In this way, it links fleshy root enlargement with stress-defense mechanisms (Li et al., 2022). Radish ICE1-like factors, such as RsICE1, are connected to the widely conserved ICE1-CBF-COR regulatory module found in many plant species. Heterologous expression of RsICE1 in rice enhances cold tolerance by increasing soluble sugar and proline accumulation and reducing membrane damage (Qian, He and Li, 2024).

3.5 Advances in omics studies (transcriptomics and metabolomics)

High-throughput transcriptomic technologies have played a critical role in identifying cold tolerance-related genes in radish. Comparative transcriptome analyses between cold-tolerant and cold-sensitive genotypes revealed that genes such as RsERF40, RsSPS1, RsWRKY40, RsWRKY49, RsCDF3, and RsSHRc are significantly induced under low-temperature conditions and are closely associated with cold-tolerant phenotypes. Therefore, these genes are considered important regulators of cold tolerance (Chen et al., 2025a). In addition, genome-wide analyses of gene families such as RsCDF and RsGRAS have identified several cold-induced members and revealed their expression dynamics during different stages of fleshy root development.

Compared with transcriptomics, metabolomic research in radish is still at a relatively early stage. However, integrated transcriptomic-metabolomic studies in other crops have revealed common patterns. Cold-tolerant genotypes generally accumulate higher levels of soluble sugars, amino acids, polyamines, flavonoids, and lignin-related metabolites. At the same time, their transcriptional regulatory networks are significantly enriched in carbohydrate metabolism, phenylpropanoid/flavonoid biosynthesis pathways, hormone signaling pathways, MAPK cascades, and ROS scavenging systems (Jian et al., 2020; Wang et al., 2021; Gao et al., 2022).

With the increasing application of multi-omics technologies in radish research, researchers are gradually establishing a systems biology framework that links morphological traits, physiological indicators, and specific regulatory genes. This framework not only helps clarify the molecular mechanisms underlying cold tolerance in radish but also accelerates breeding programs based on Marker-Assisted Selection (MAS) and Genomic Selection (GS) for the development of cold-tolerant winter radish cultivars.

4 Cold Tolerance Germplasm Resources and Breeding of Radish

4.1 Diversity of Chinese radish germplasm resources

Radish germplasm resources provide the essential genetic foundation for developing new varieties with strong stress tolerance, high yield, and superior quality. China is one of the major centers of radish diversity and production worldwide, with a cultivation area of about 1.2 million hectares and an annual production exceeding 40 million tons (Xing et al., 2024). At present, more than 2 000 radish germplasm accessions have been collected and conserved in Chinese germplasm repositories, of which approximately 95% are domestic landraces. This reflects the rich in situ genetic diversity and long domestication history of radish in China (Wang et al., 2018). Population genetic studies based on single nucleotide polymorphism (SNP) and structural variation (SV) markers have shown that radish resources from China and other East Asian regions form the major genetic groups. Clear genetic differentiation exists between these groups and European or other regional types. However, relatively frequent gene flow has also been observed among some subpopulations, accompanied by a certain risk of genetic erosion (Li et al., 2023a).

4.2 Identification of cold-tolerant landrace resources

Landraces are generally defined as heterogeneous populations that have evolved through long-term farmer selection under specific ecological, geographical, and cultivation conditions. They are valuable genetic resources for obtaining adaptive traits such as tolerance to abiotic stresses. In radish research, systematic evaluations conducted across different seasons and locations have identified excellent germplasm resources with desirable agronomic traits and strong stress resistance. For example, long-term trials carried out in Jinan, Yangling, Harbin, and other regions screened multiple germplasm accessions with outstanding overall performance based on yield, stress tolerance, and disease resistance (Qu et al., 2002). The conservation of radish germplasm resources in China places particular emphasis on collecting and preserving landraces from their regions of origin as well as resources representing different ecological types. These materials exhibit abundant phenotypic and biochemical variation.

4.3 Conventional breeding methods (selection breeding and hybrid breeding)

Traditional radish breeding mainly focuses on target traits such as high yield, early maturity, late bolting, cold tolerance, drought tolerance, heat tolerance, disease resistance, and high-quality fleshy roots. Through methods including mass selection and pedigree selection within landraces and local populations, as well as intraspecific and interspecific hybridization, favorable alleles can be continuously accumulated, resulting in varieties that combine multiple desirable traits that are difficult to achieve in a single genotype.

With the development of F_1 hybrid seed production systems based on self-incompatibility, identification of S haplotypes in parental lines has become an important step for efficient hybrid seed production. This approach eliminates the need for manual emasculation, greatly improves hybrid seed production efficiency, and accelerates the incorporation of complementary favorable traits, including stress tolerance, into commercial cultivars (Kumar and Kaushik, 2021). In addition, core germplasm collections established from large-scale germplasm resources have been widely used in the development of cytoplasmic male sterility (CMS) lines and new hybrid cultivars, further improving the efficiency of conventional breeding programs.

4.4 Molecular breeding strategies (marker-assisted selection and genomic tools)

In recent years, significant progress has been made in radish genomics research. High-quality reference genomes, genetic linkage maps, SNP and SV marker systems, and molecular markers associated with important agronomic traits have been continuously developed and improved (Kim et al., 2019). Molecular fingerprint maps based on SNPs and SVs can not only be used for accurate germplasm identification, genetic structure analysis, and core germplasm collection construction, but also provide important technical support for marker-assisted selection (MAS) and genomic studies.

At present, MAS technology has been successfully applied in radish disease-resistance breeding. Using 275 core radish germplasm accessions collected from 30 provinces in China as well as Russia, Germany, South Korea, and other countries, Ma et al. (2024) conducted artificial inoculation with Race 4, the dominant physiological race of *Plasmodiophora brassicae* in China. Disease resistance levels were evaluated using the disease index (DI). Significant differences in clubroot resistance were observed among the germplasm resources. Six highly resistant accessions and 50 resistant accessions were identified. Some materials originating from Sichuan Province, Russia, and Germany showed stable and high levels of resistance (Figure 1). The study further analyzed the geographic distribution and horticultural characteristics of these resistant germplasms and found that resistant resources were relatively abundant in southern regions. In addition, the highly resistant materials exhibited considerable genetic diversity in leaf type, fleshy root shape, and root color. Previously reported clubroot-resistant SSR molecular markers were then used to evaluate the highly resistant materials. The results indicated that these accessions possessed genetic characteristics different from those of known resistant materials, suggesting that they may carry novel resistance genes. Finally, several highly resistant accessions were crossed with elite cultivated varieties, resulting in a number of hybrid progenies with breeding potential.

At the same time, genome-wide association studies (GWAS) and transcriptome analyses have identified several important genes and transcription factors involved in cold tolerance and fleshy root development, including RsERF40 and the RsWRKY40-RsSPS1-CBF regulatory module. These findings provide potential targets for improving cold tolerance through MAS and genomic selection while maintaining normal fleshy root growth (Li et al., 2023b).



Figure 1 Phenotypic comparison between high-resistance and high-sensitivity seedlings. (a-f) Highly resistant (HR); (g-i) highly susceptible (HS). Bar scale = 1 cm (Adopted from Ma et al., 2024)

4.5 Major achievements and limitations of breeding research

Substantial progress has been achieved in radish breeding with respect to yield, quality, disease resistance, and environmental adaptability. In some breeding programs, more than half of the released cultivars have become F_1 hybrids developed using CMS technology and molecularly identified core germplasm resources. Among these achievements, clubroot resistance breeding is considered a successful example. Through the integration of diverse germplasm resources, phenotypic screening, and molecular marker technologies, breeders have not only enriched the resistance gene pool but also developed several new disease-resistant cultivars.

However, some cultivated populations still face problems related to relatively narrow genetic backgrounds and ongoing genetic erosion. In terms of cold-tolerance breeding, although the molecular regulatory mechanisms and key regulatory genes are being gradually clarified, relatively few cold-tolerant winter radish cultivars have been widely adopted in production. This is mainly due to the incomplete development of molecular markers associated with cold tolerance, the complex quantitative inheritance of cold-tolerance traits, and the lack of high-quality phenotypic data collected across multiple environments (Chang-Brahim et al., 2024; Ray et al., 2025).

5 Characteristics of Major Cold-Tolerant Radish Cultivars

5.1 Criteria for cold tolerance evaluation

The evaluation of cold tolerance in radish cultivars usually considers their survival ability under low-temperature conditions, production stability, and the ability to maintain agronomic and quality traits. Key evaluation indicators include stable seed germination and plant establishment under unfavorable low-temperature environments, reduced bolting and disease incidence, and the ability to produce marketable fleshy roots during cool seasons, under protected cultivation, or in low-temperature regions. In addition, yield stability (fleshy root yield per unit area and proportion of marketable roots), as well as the maintenance of root morphology, storage performance, and sensory quality, are widely used as important indicators for assessing cultivar adaptation to winter or off-season cultivation environments.

5.2 Morphological and agronomic traits

Cold-tolerant or winter-adapted radish cultivars generally show vigorous vegetative growth and strong fleshy root development under cool environmental conditions. Studies conducted across different ecological environments have shown that plant height, leaf number, leaf area, root length, root diameter, and individual root weight are important agronomic traits for selecting superior cultivars (Singh et al., 2021; Lahari and Tripathi, 2023; Thakur et al., 2023).

For example, under cool or protected cultivation conditions, the cultivars Ivory White F1 and Okura can achieve fleshy root yields of approximately 30~54 t·ha⁻¹, while also producing longer roots and larger root diameters (Shrestha et al., 2021).

The Chinese radish cultivar Serdtse Podmoskovya, developed in Russia, is characterized by a medium growth period (65~75 d), a high marketable root rate (81%~89%), and a relatively large individual root weight (281~533 g). It has shown good production performance under both open-field and protected cultivation conditions (Stepanov, 2023). Genetic diversity analyses have further demonstrated that radish germplasm resources exhibit extensive variation in growth duration, root shape (ranging from round to cylindrical), and biomass allocation patterns.

5.3 Quality characteristics (flavor, texture, and nutritional composition)

Cold-tolerant radish cultivars intended for winter markets must not only possess strong environmental adaptability but also meet consumer expectations for quality. Important quality traits include uniform root shape and size, smooth skin, crisp and tender flesh, and a moderate pungent flavor.

Under shade-net or off-season cultivation conditions, the hybrid cultivars Ivory White F1 and Mino Early Long White F1 showed relatively high root dry matter content (approximately 7.6%), high ascorbic acid content (approximately 19.5 mg/100 g), and high total soluble solids content (approximately 6 °Brix). These cultivars also received favorable consumer ratings for pungency and overall flavor (Dahal et al., 2020).

The cultivar Serdtse Podmoskovya produces white, juicy fleshy roots with a mildly pungent taste. Under winter production conditions, its dry matter content ranges from 6.3% to 11.0%, total sugar content from 2.6% to 3.2%, and ascorbic acid content is approximately 19~20 mg% (Stepanov, 2023). Late-maturing, large-root winter cultivars generally contain higher levels of dry matter and vitamin C, whereas early-maturing, small-root cultivars tend to have lower dry matter content but still maintain desirable ascorbic acid levels (Kurina et al., 2021).

5.4 Representative cultivars suitable for southern winter conditions

Studies conducted under various cool-season and off-season cultivation environments have identified several cultivars suitable for winter or protected production systems. Under spring and off-season cultivation conditions in Nepal, Ivory White F1 consistently produced the highest fleshy root yields and exhibited excellent quality characteristics in both net-house and shaded cultivation systems.

In addition, comparative trials conducted under winter protected cultivation conditions in Wuhan identified several Korean spring radish cultivars that demonstrated good yield and quality performance within autumn–winter protected production systems (Wan, 2010).

5.5 Comparative performance under open-field and protected cultivation conditions

Superior cold-tolerant cultivars are generally able to achieve higher and more stable yields than local check cultivars during cool-season or off-season cultivation while maintaining desirable quality characteristics.

Under shade-net and off-season production environments, Ivory White F1 produced fleshy root yields of approximately 31 t·ha⁻¹ and outperformed other improved and hybrid cultivars in root length, root circumference, dry matter content, vitamin C content, and consumer acceptance (Dahal et al., 2020).

In winter open-field trials, compared with the commonly grown cultivar Mino Early, Okura increased yield by approximately 49%, while Miyasige increased yield by approximately 22%. Both cultivars maintained good root size and attractive external appearance (Shrestha et al., 2021).

6 Winter Production Cultivation Techniques

6.1 Optimal sowing time and planting density

By properly adjusting sowing time and planting density, radish can achieve stable production under low-temperature conditions. Model analyses and long-term simulation studies have shown that optimizing sowing dates together with proper irrigation and fertilization management can significantly improve radish yield and resource-use efficiency. This indicates that sowing time should be matched with local climatic conditions and should be selected to avoid severe low-temperature damage while ensuring sufficient accumulated temperature for fleshy root development (Zhang et al., 2021).

Experimental results under different seasonal conditions further demonstrated that direct seeding with a smaller plant spacing (approximately 10 cm) is favorable for aboveground vegetative growth, whereas a wider spacing (approximately 20 cm) significantly increases root diameter, root length, and individual root weight. These findings suggest a density trade-off between leaf growth and fleshy root yield (Hudu et al., 2025). Therefore, in winter production, sowing dates should be arranged according to local cold-wave patterns to avoid periods of extreme low temperatures. At the same time, an appropriate planting density should be adopted to ensure rapid canopy closure and improved ground coverage while providing sufficient space for root enlargement.

6.2 Soil preparation and nutrient management

Radish is highly responsive to soil fertility, and improper fertilization is one of the major reasons for low nutrient-use efficiency in radish production in China. The combined application of chemical fertilizers with organic and biofertilizers, such as farmyard manure, spent mushroom substrate, nitrogen-fixing bacteria (*Azotobacter*), and phosphate-solubilizing bacteria, can significantly increase the availability of nitrogen (N), phosphorus (P), and potassium (K) in the soil. This practice promotes fleshy root growth, increases yield, and improves soil health, showing much better results than the use of chemical fertilizers alone (Shilpa et al., 2023).

In recent years, the Nutrient Expert system and nutrient requirement models based on the QUEFTS framework have enabled the accurate estimation of balanced nitrogen, phosphorus, and potassium requirements according to the nutrient demand per unit yield. These tools provide scientific support for fertilization decisions under different soil and climate conditions, thereby improving yield and economic returns, enhancing nutrient-use efficiency, and reducing environmental risks associated with excess nitrogen and phosphorus accumulation (Zhang and Ullah, 2022).

Deep plowing and careful seedbed preparation before sowing are beneficial for uniform seed emergence and early root development. These practices are particularly important for successful crop establishment under winter low-temperature conditions.

6.3 Irrigation strategies under low-temperature conditions

During winter radish production, evapotranspiration is generally low. However, maintaining suitable soil moisture remains a key factor for normal plant growth and nutrient uptake. Optimized irrigation management can reduce irrigation water use by approximately one-third to one-half while maintaining or even increasing yield, and it can also significantly decrease the risk of nitrate leaching (Gan et al., 2023).

Drip irrigation experiments have shown that maintaining moderate soil water potential (generally around 7~12 kPa) under suitable mulching conditions results in the best fleshy root growth, fresh weight accumulation, and economic returns. Both water deficit and excessive moisture can reduce production performance (Santos et al., 2022). Under protected cultivation conditions, moderate deficit irrigation combined with appropriate nitrogen application can maintain yield while improving nitrogen-use efficiency and reducing environmental impacts.

During winter irrigation, prolonged soil saturation should be avoided to prevent root injury under low-temperature conditions. In addition, irrigation should preferably be carried out during the warmer periods of the day to minimize cold damage to root growth.

6.4 Application of protected cultivation measures (mulching, tunnels, and greenhouses)

Protected cultivation is an important approach for reducing low-temperature stress and ensuring safe radish production during winter. Plastic mulches of different colors can increase rhizosphere temperature and soil heat accumulation. Transparent plastic mulch usually provides the strongest warming effect and can significantly increase root length, root diameter, and root weight while effectively reducing premature bolting caused by temperatures below 10 °C during early spring (Lee and Park, 2020).

Black plastic mulch and nonwoven fabric covers can also improve plant growth and yield. Under suitable soil moisture tension conditions, black plastic mulch generally provides higher production efficiency and economic benefits than bare-soil cultivation. In addition, organic mulches and crop residues, such as straw and by-products from Brazilian palm processing, can improve the soil moisture and temperature environment, thereby enhancing radish growth and productivity under protected cultivation systems (Gomes et al., 2020).

Low tunnels, high tunnels, and combined low-tunnel plus high-tunnel systems can significantly increase vegetable yields during cool seasons and can maintain stable production even under freezing conditions (Shiwakoti et al., 2018). For radish production, polyethylene low tunnels can improve leaf nutrient status, increase dry matter accumulation, and enhance fleshy root yield. When combined with foliar silicon application, the effects on cold tolerance and yield improvement become even more pronounced (Alhasnawi and Al-Bayati, 2023; Al-Bayati and Alhasnawi, 2025).

In seed production systems, winter greenhouses are commonly equipped with heated or insulated seedbeds and plastic covering facilities for elite plant propagation, ensuring early transplanting and protection from frost damage.

6.5 Integrated pest and disease management in winter

Winter production does not completely eliminate pest and disease problems; instead, it changes the timing and types of pests and diseases that occur. In radish seed production, protected facilities such as greenhouses and plastic tunnels still require strict weed, pest, and disease management, and pesticides should be used in accordance with relevant national regulations and approved pesticide lists.

In both open-field and protected winter cultivation systems, mulches and cover crops can serve as important components of integrated management strategies. Dead mulches not only suppress weed growth but also regulate soil moisture and temperature, thereby improving crop performance. In addition, winter cover crops dominated by

radish can effectively suppress overwintering annual weeds that emerge in autumn and early spring, reducing the need for herbicide applications before planting subsequent crops.

In vegetable rotation systems and high-tunnel production systems, overwintering cover crops, including radish, can also promote soil biological activity and nitrogen cycling without reducing the yield of subsequent cash crops. These benefits contribute to long-term soil health maintenance and improve the resilience of agricultural systems to environmental stress (Perkus et al., 2022; Elhakeem et al., 2023; Wang et al., 2023).

7 Case Studies of Winter Radish Production Systems

7.1 Case study in the Yangtze River delta region

The Yangtze River Delta region, including Shanghai and Zhejiang, is one of the major autumn-winter radish production areas in China. It is characterized by a temperate-subtropical monsoon climate and highly intensive vegetable rotation systems. Field experiments conducted in Zhejiang and Shanghai showed that radish is commonly grown as a rotational crop after rice or leafy vegetables. Although its growing period is relatively short, the input levels of nitrogen (N), phosphorus (P), and potassium (K) are generally high (Zhang et al., 2019b). The use of scientific nutrient management tools such as the QUEFTS model and Nutrient Expert for balanced fertilization can significantly improve fleshy root yield and nutrient use efficiency compared with traditional farmer fertilization practices (Figure 2). These results indicate that science-based fertilization management plays an important role in supporting the high-input winter production systems in this region.

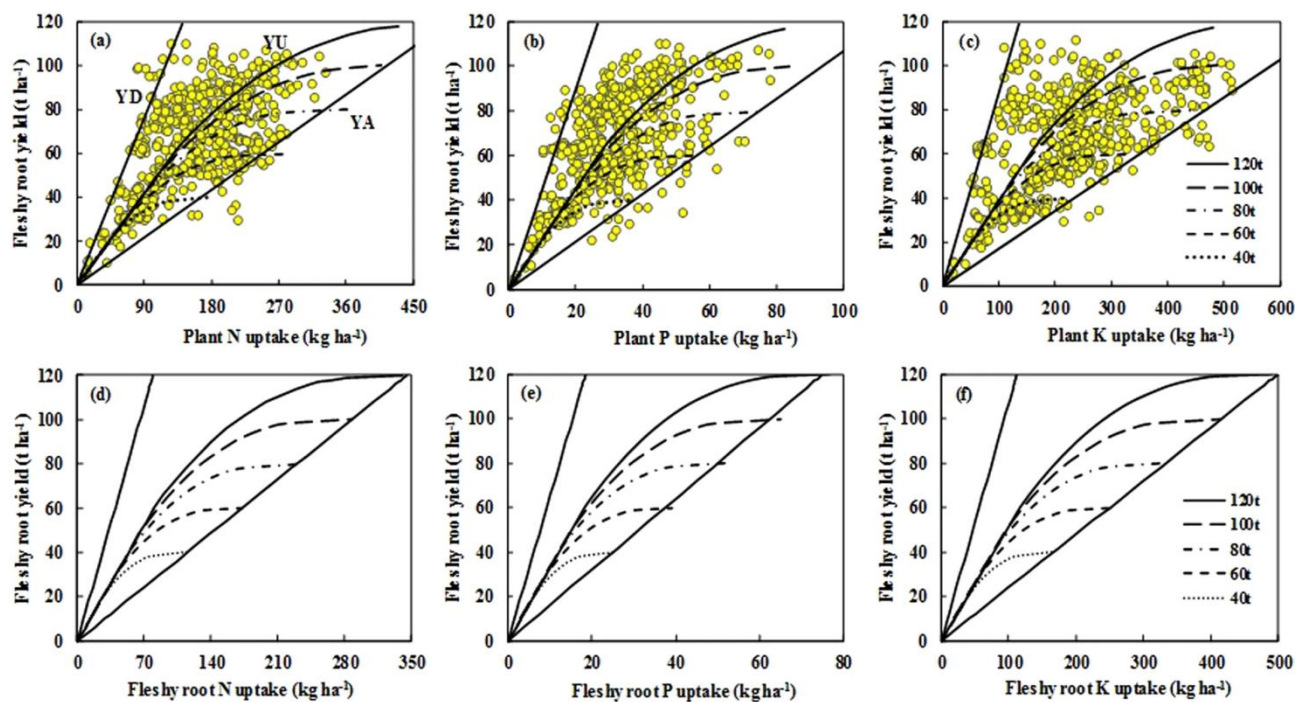


Figure 2 Relationships between fleshy root yield and N, P, and K accumulation in the total plant dry matter at maturity (a-c) and fleshy root N, P, and K removal in fleshy root dry matter (d-f) under different potential yields predicted by the QUEFTS model. YD, YA, and YU represent the maximum dilution, maximum accumulation, and balanced uptake of N, P, and K in the total plant dry matter or in the fleshy roots dry matter, respectively. These parameters were calculated by the QUEFTS model after excluding the upper and lower 2.5 percentiles of all internal efficiency data ($HI \geq 0.4$). The potential yield ranged from 40 to 120 t ha⁻¹ (Adopted from Zhang et al., 2019b)

7.2 Case study in southern China (e.g., Guangdong and Guangxi)

Subtropical regions such as Jiangxi and Chongqing, which represent the warm and humid ecological conditions of southern China, widely practice autumn-winter radish production. These areas are characterized by relatively mild temperatures and considerable variation in soil conditions. Soil organic matter content and available nitrogen, phosphorus, and potassium levels differ greatly among locations. Therefore, site-specific nutrient and water management strategies are required to fully realize yield potential according to local soil characteristics (Zhang et

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·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.

8.4 Strengthening regional breeding and extension systems

Studies on genetic diversity and the development of core germplasm collections indicate that greater attention should be given to the strategic use of germplasm resources from different geographic regions as well as wild relatives during breeding programs. At present, several regional breeding projects have successfully combined genomic technologies, controlled-environment screening methods (such as artificial-light cultivation), and field evaluations to develop high-performance radish lines suitable for protected cultivation and cold-region production (Sinyavina et al., 2023). In the future, stronger collaboration among research institutions, agricultural extension services, and farmers will be needed to accelerate the transfer and application of research results in winter radish production.

Author Contributions

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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