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 ℃~24/18 ℃. 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 ℃~8 ℃, while the annual mean temperature in many areas ranges from 14 ℃ to 18 ℃. 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 ℃ (Yu et al., 2022).