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 (H_2O_2) (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).