More specifically, yield instability arises from the interaction of weather, soil fertility, and agronomic or biological stress. Cowpea evidence showed that GEI was associated with temperature, rainfall, relative humidity, maturity, and yield components, indicating that climatic variation directly alters performance rankings among genotypes. Soil effects can be equally important: in West African cowpea, year was the largest source of annual variation, but differences in soil nitrogen and available phosphorus explained much of the yield contrast among soil types under the same rainfall regime. Other legume studies further identify moisture stress, poor soil fertility, disease, insect pressure, weak management, and lack of adaptable varieties as recurrent constraints on stable production (Eskezia et al., 2025). For Zhejiang, this suggests that the comprehensive evaluation of yield stability should not stop at ranking crops statistically, but should also link those rankings to rainfall variability, soil conditions, cropping management, and species-specific stress tolerance. Overall, the comprehensive evaluation of yield stability among different legume crops in Zhejiang should integrate statistical indices, multi-model validation, and environmental interpretation. This is the most appropriate basis for identifying legume crops that combine relatively high yield with stable performance across Zhejiang's diverse ecological conditions.

## 6 Mechanisms Underlying Yield Stability Formation in Legume Crops

### 6.1 Climate adaptability and yield stability mechanisms

Climate adaptability is a primary mechanism underlying yield stability in legume crops because climate change increasingly exposes legumes to overlapping stresses rather than isolated constraints. Concurrent heat and drought stress disrupt growth, development, and yield formation, and these combined stresses are especially damaging during reproductive stages because they shorten the crop life cycle and alter seed number, size, and composition. More general synthesis across crops shows that drought-heat episodes reduce harvest index and intensify yield loss when they occur during flowering and seed filling, which explains why stable-yielding legumes must maintain reproduction under seasonal weather variability. For Zhejiang, where high temperature, heavy rainfall, and intermittent summer drought can alternate within the same season, yield stability is therefore closely tied to the capacity of different legume species to buffer reproductive processes against fluctuating hydrothermal conditions.

This buffering capacity depends on coordinated physiological and molecular stress responses rather than on a single tolerance trait. Legumes exposed to combined heat and drought rely on osmolytes, antioxidants, and stress-responsive genes, while signaling pathways involving $Ca^{2+}$, reactive oxygen species, and transcriptional regulators help integrate stress perception and adaptive responses (Priya et al., 2025). Drought tolerance also depends on traits such as improved root system architecture, stomatal regulation, antioxidant defense, and solute accumulation, which together reduce water loss and oxidative injury while sustaining carbon assimilation under stress. These findings indicate that climate adaptability contributes to yield stability when legumes can maintain source-sink balance, reproductive success, and resource use efficiency across variable weather conditions rather than only under average years.

### 6.2 Physiological and ecological characteristics

Stable production in legumes is strongly associated with physiological traits that sustain nitrogen acquisition and biomass formation under variable field conditions. Biological nitrogen fixation is central because it supports plant nutrition while reducing dependence on external nitrogen inputs, and its effectiveness depends on successful nodulation and rhizosphere functioning (Qiao et al., 2024). Long-term diversification experiments showed that legume rhizodeposition can reshape rhizosphere metabolites and microbial functions, thereby enhancing the growth and nitrogen-fixing activity of free-living bacteria and increasing nodulation by symbiotic Bradyrhizobium. This means that yield stability is not only a property of the plant itself, but also of the plant-microbe system that supports nitrogen supply across different soil and management environments.

Ecological interactions further strengthen stable production by improving root conformation, nitrogen transfer, and resource partitioning. In mixed cropping across three ecological zones, legumes showed higher nodulation, better root-system configuration, greater aboveground dry matter, and enhanced nitrogen fixation, while the main drivers of atmospheric nitrogen fixation included cropping pattern, ecological zone, soil nitrogen status, microbial