

Review Article

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Comparison of Yield Stability among Different Legume Species in Zhejiang

Yu Zhan ✉

Zhejiang Green Giant Biotechnology Co., Ltd., Jinhua, 321071, Zhejiang, China

✉ Corresponding author: 3601303@qq.comGenomics and Applied Biology, 2026, Vol.17, No.5 doi: [10.5376/gab.2026.17.0021](https://doi.org/10.5376/gab.2026.17.0021)

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Abstract Legume crops play an important role in ensuring food security, improving soil fertility, and promoting sustainable agricultural development. However, yield instability caused by climatic fluctuations, environmental stresses, and management variations remains a major challenge for legume production in Zhejiang Province. This study aims to systematically compare the yield stability of different legume crops in Zhejiang by integrating long-term yield data, ecological information, and statistical evaluation methods. The research will analyze yield variation characteristics, stability differences, and environmental adaptability among major legume crops, including soybean, broad bean, pea, mung bean, and common bean. Multiple stability assessment approaches, such as coefficient of variation, AMMI model, GGE biplot analysis, and multivariate statistical methods, will be applied to identify crops with high yield stability and broad ecological adaptability. Furthermore, the physiological, ecological, and genetic mechanisms underlying yield stability will be explored, with emphasis on climate adaptation, resource utilization efficiency, and genotype-environment interactions. A case study of typical ecological regions in Zhejiang will be conducted to reveal regional differences in legume production stability and provide targeted optimization strategies. The findings will contribute to the selection of stable-yielding legume varieties, improvement of precision cultivation practices, and development of climate-resilient legume production systems in Zhejiang Province.

Keywords Legume crops; Yield stability; Genotype-environment interaction; Ecological adaptability; Zhejiang Province

1 Introduction

Legume crops are strategically important to agricultural production, human nutrition, and the ecological transformation of cropping systems in Zhejiang. Legumes provide protein-rich grain and diverse food uses, and many species also contribute to fodder, green manure, and functional food development (Jarecki and Migut, 2022). Their wider value lies not only in seed production but also in their role in sustainable intensification, because legumes fix atmospheric nitrogen through symbiosis, improve soil fertility, reduce synthetic fertilizer demand, and enhance rotational performance of subsequent crops. Meta-analytic and review evidence further shows that legumes support self-sufficiency in plant protein, reduce greenhouse-gas emissions relative to non-legume crops, improve biodiversity and soil health, and fit well with conservation-oriented farming systems. In China, food legumes have long been embedded in rotation, intercropping, and mixed-cropping systems, and the country remains a leading producer of pea, faba bean, mung bean, and adzuki bean. At the same time, China's vast territory and complex ecological conditions create strong spatial heterogeneity in legume adaptation, while changing market conditions have reduced the profitability and planting area of some dry grain legumes, increasing the need to identify species and cultivars with better productivity and stability under local conditions. Zhejiang is characterized by humid subtropical monsoon conditions, diverse micro-environments, and intensive multiple-cropping systems, so production risk is shaped not only by average yield level but by the consistency of yield across years, sites, and management situations. For this reason, evaluating yield stability among legume species is more useful for regional crop and variety recommendation than comparing yield in a single environment alone. This focus is also supported by broader agronomic evidence showing that stable performance across environments is a central target in crop improvement, because yield is a complex quantitative trait jointly controlled by genotype, environment, and their interaction (Islam et al., 2021). A genotype or species is considered practically valuable when it combines relatively high mean yield with low fluctuation across environments, thereby reducing production risk and supporting reliable legume expansion in diversified cropping systems (Baraki et al., 2020).

Research in China and abroad has shown that genotype $\times$ environment interaction (GEI) is the key scientific issue underlying yield instability and the differential ranking of materials across test sites. GEI reflects the fact that genotypes behave differently under different environmental conditions, and understanding this interaction is essential for predicting adaptation, identifying ideal testing environments, and selecting either broadly adapted or specifically adapted materials. In legumes, this phenomenon has been repeatedly confirmed. In Ethiopian cowpea, environments, genotypes, and GEI all had significant effects on grain yield, and GEI accounted for a larger share of variation than genotype alone, indicating strong crossover responses among test locations. In Ugandan cowpea, environment contributed the largest share of grain-yield variation, and GEI was associated with weather variables such as temperature, rainfall, and humidity as well as yield components (Mbeyagala et al., 2021). In mung bean, significant effects of genotype, environment, and GEI have also been reported, both in drought-tolerance evaluation in Bangladesh and in multi-year testing in northern Ethiopia, confirming that stable high-yielding selection requires trials over years and locations. Comparable conclusions have been reported in faba bean, lentil, Bambara groundnut, and field pea, where multi-environment experiments were necessary to identify stable, high-yielding genotypes and to distinguish widely adapted materials from those suited to specific mega-environments (Ghaffar et al., 2023). Methodologically, AMMI and GGE biplot have become the most widely used tools for this purpose because ANOVA alone can detect significance but cannot adequately resolve the non-additive structure of GEI. AMMI emphasizes additive main effects and multiplicative interaction structure, whereas GGE integrates genotype main effects with GEI and provides intuitive graphical judgment of “which-won-where,” mean-versus-stability, and environment representativeness (Mullualem et al., 2024). These methods have been applied successfully not only in legumes such as cowpea, mung bean, lentil, faba bean, Bambara groundnut, and pea, but also in other crops, where they effectively identify ideal genotypes, discriminating test sites, and mega-environment structure. At the same time, recent work suggests that stability evaluation can be strengthened by combining AMMI and GGE with complementary indices such as ASV, GSI, WAASB, WAASBY, or MTSI, especially when high yield must be balanced with multiple traits or adaptation goals. Another important insight is that the long-standing belief that legumes are inherently unreliable is overstated: long-term experiments across northern Europe showed that grain legume yields were as reliable as those of other spring-sown crops when stability was assessed appropriately, although agronomic improvement is still needed to raise both yield level and stability.

Against this background, the objective of this study is to compare the yield stability of different legume species under Zhejiang conditions and to provide an evidence base for regional species selection, variety deployment, and optimized cropping-system arrangement. More specifically, the study aims to determine whether different legume species differ significantly in mean yield and stability, to quantify the relative contributions of species effects, environment effects, and their interaction to yield variation, and to identify species or materials with either broad adaptability or specific adaptation to particular production environments. This objective follows the common logic of multi-environment crop evaluation, in which significant GEI implies the need to evaluate genotypes across diverse sites before recommendation. The technical framework therefore includes multi-environment field trials across representative ecological zones or seasons in Zhejiang, standardized measurement of grain yield and key agronomic traits, and joint statistical analysis combining analysis of variance with AMMI and GGE biplot methods. In this framework, ANOVA is used first to test the significance of species, environment, and interaction effects, while AMMI is used to partition interaction structure and assess general adaptability, and GGE biplot is used to visualize winning species, ideal genotypes, representative test sites, and possible mega-environment differentiation. Where necessary, stability indices can be introduced to integrate mean yield and stability ranking, improving the robustness of recommendation decisions. Because species differ in both production potential and functional traits, the interpretation of results should also consider their broader agronomic roles: soybean often shows high seed and protein yield, faba bean can be productive but more variable across years, white lupin may outperform other lupins in yield, and cowpea and mung bean can maintain useful forage production even under drought-related stress. Ultimately, by integrating productivity, stability, and ecological value, this study is expected to support the selection of legume species that are better suited to Zhejiang’s diverse environments and cropping systems, thereby improving farmer resilience, land-use efficiency, and the sustainable development of legume-based agriculture.

2 Production Status and Ecological Characteristics of Legume Crops in Zhejiang Province

2.1 Planting structure and regional distribution of legume crops in Zhejiang Province

Legume crops occupy an important but structurally differentiated position within Chinese cropping systems, and Zhejiang should be understood within this broader pattern. In China, pulses are commonly embedded in rotation, intercropping, and mixed-cropping systems, which gives legumes value not only as food crops but also as flexible components of diversified farmland use. The major food legume groups grown nationally include pea, faba bean, common bean, mung bean, adzuki bean, and cowpea, together with a wider set of locally distributed minor legumes, indicating that species choice is closely tied to local ecological and market conditions. For Zhejiang, this implies a planting structure in which soybean, mung bean, adzuki bean, cowpea, and vegetable-type legumes are more likely to coexist than to form a single dominant dry-grain system, especially under intensive land use and multiple-cropping conditions. At the national scale, soybean planting is also organized by agroecological zones, and the middle-lower Yangtze River double-cropping ecoregion is recognized as one of the major soybean production zones in China, which places Zhejiang within a wider south-eastern soybean adaptation belt (Mei et al., 2024).

From the perspective of spatial distribution, legume planting in Zhejiang is likely to show obvious regional heterogeneity because crop layout in China generally responds to both natural suitability and comparative economic return. Studies of crop planting structure in other Chinese regions show that spatial allocation is shaped by climate, geography, and population-related factors, and that optimizing crop distribution requires attention to county- or regional-scale differences rather than uniform provincial planning. Remote-sensing evidence from major grain regions further shows that higher-benefit crops tend to concentrate in locations with better accessibility and stronger production conditions, while less competitive crops contract or shift spatially when relative profitability declines (Liu and Wang, 2022). Applied to Zhejiang, this suggests that vegetable legumes and fresh-use beans are more likely to cluster in peri-urban plains and developed horticultural belts, whereas dry-grain legumes are more likely to persist in hilly areas, upland fields, or as rotation crops within smaller and more fragmented farming systems. In recent decades, reduced profits have caused decreases in the sowing area of some dry food legumes in China, while vegetable food legumes have expanded because of stronger market demand and shorter growth duration (Figure 1).

2.2 Agro-ecological characteristics

Zhejiang belongs to China's subtropical agricultural zone, and its agro-ecological background is generally characterized by abundant heat and rainfall occurring in the same season, a combination that strongly supports intensive cropping but also increases ecological sensitivity. Research on China's subtropical region shows that this broad zone has synchronous hydrothermal conditions and serves as one of the country's traditional agricultural cores (Chen et al., 2025). Comparable studies from humid subtropical production areas show annual precipitation concentrated in the April-October growing season and high overlap between peak temperature and rainfall. For legume crops in Zhejiang, such conditions are generally favorable for rapid biomass accumulation and multiple cropping, but they also mean that excess moisture, cloudy-rainy periods, and strong seasonal fluctuations can affect sowing dates, flowering, pod setting, and harvesting stability.

At the same time, Zhejiang's ecological suitability for crops is shaped not only by climate but also by topography and soils. A land ecological suitability analysis conducted specifically in Zhejiang selected annual mean temperature, accumulated temperature above 10 °C, extreme low temperature frequency, humidity, slope, aspect, altitude, soil type, and soil texture as key determinants of crop distribution, showing that provincial crop suitability depends on the joint action of climate, terrain, and edaphic factors. The same study demonstrated that GIS-based suitability zoning can effectively reproduce the current distribution of crops in Zhejiang, indicating strong spatial differentiation in ecological adaptation across the province. This is especially relevant for legumes because the province includes plains, river valleys, coastal zones, and hilly or mountainous land, so temperature resources, drainage conditions, and soil physical properties are unlikely to be uniform. In such a setting, differences in ecological niche among legume species are expected to translate directly into differences in regional yield level and yield stability.

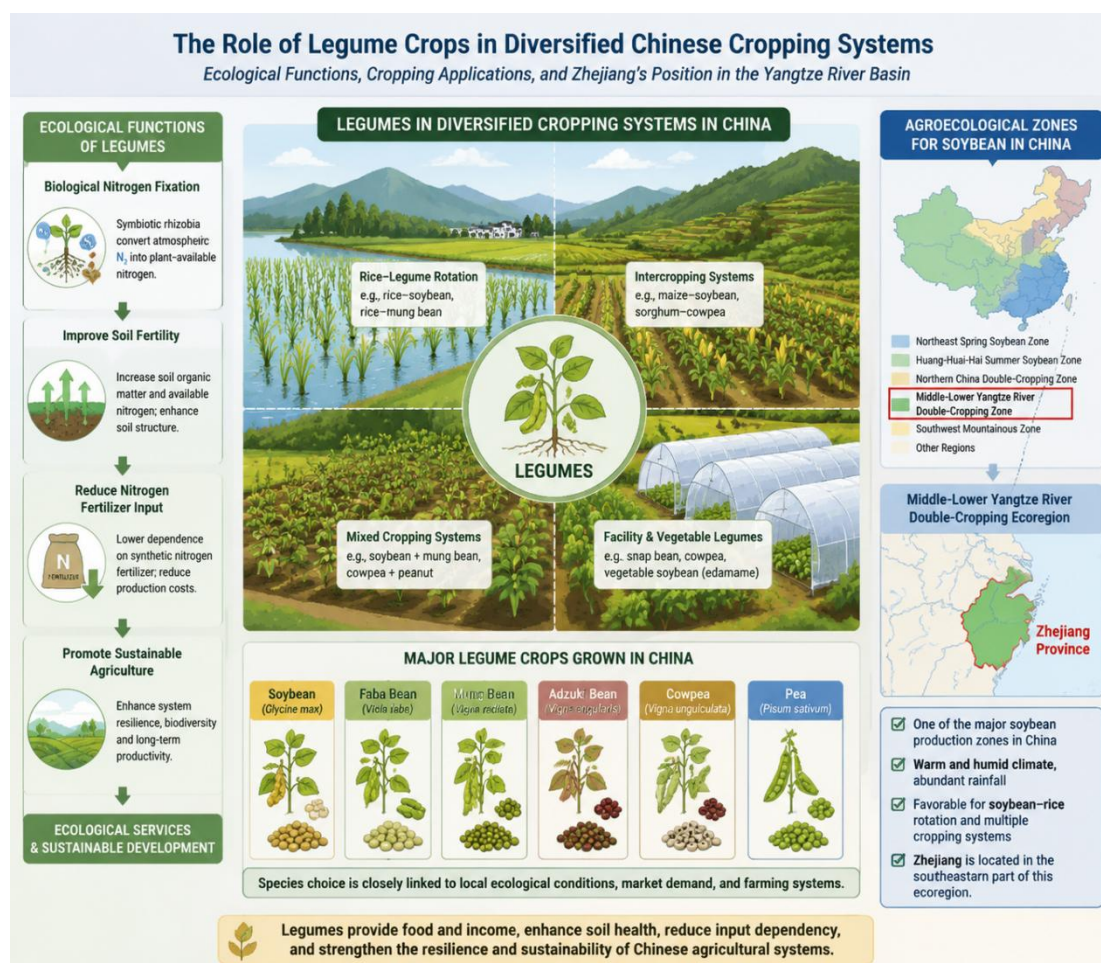


Figure 1 Conceptual framework illustrating the ecological functions of legume crops within Chinese diversified cropping systems and the position of Zhejiang Province within the middle-lower Yangtze River soybean adaptation zone

2.3 Limiting factors

The limiting factors affecting legume production in Zhejiang are multiple and should be understood as the interaction of abiotic, biotic, management, and socio-economic constraints. Comparative work on food-crop systems identifies these four categories as the main contributors to yield gaps, with the specific combination varying by crop and farming system. More general crop-production research similarly shows that low productivity commonly results from drought or excess moisture, soil constraints, diseases and insect pests, lack of improved varieties, weak infrastructure, and insufficient input efficiency. Under Zhejiang conditions, this means that yield instability in legumes is unlikely to arise from a single stress; rather, it is likely to reflect the combined effects of humid subtropical weather, fragmented land use, uneven soil conditions, and differences in management intensity across regions. Because precipitation and temperature are central drivers of yield variation in Chinese cropping systems, climate-related fluctuations remain a basic source of production risk (Gao et al., 2022).

For legume crops specifically, several constraints are especially relevant. Mungbean, one of the representative short-season legumes suited to diversified systems, is constrained by insect pests, diseases, drought, waterlogging, salinity, and heat stress, illustrating the broad stress spectrum that legume crops may face in production. In China, another major bottleneck is continuous cropping: because limited arable land often forces repeated planting of the same legume on the same plot, continuous-cropping obstacles have become common and can seriously impair yield formation through soil degradation and crop-soil interaction problems (Lei et al., 2023). This issue is highly relevant to Zhejiang's intensive farming context, where land scarcity and high cropping intensity may encourage short rotations or repeated use of the same fields for similar legume types. In addition, subtropical production systems can face nutrient surplus, declining nutrient-use efficiency, and soil acidification under intensive management, suggesting that sustainable improvement of legume production in Zhejiang depends not only on

varietal adaptation, but also on better rotation design, soil management, and input regulation. Overall, the production status and ecological characteristics of legume crops in Zhejiang are defined by a diverse planting structure, a humid subtropical resource base, and multiple interacting production constraints. These features make Zhejiang a suitable setting for comparing yield stability among legume species across contrasting ecological and management environments.

3 Data Sources and Methods for Yield Stability Evaluation

3.1 Data sources and research materials

The yield stability evaluation in this study should be based on multi-environment trial data, because this design is the standard framework for judging crop adaptability and stable performance across contrasting production conditions. In legume research, multi-environment trials have been used to compare grain yield across locations, seasons, and years so that genotype or species performance can be evaluated under realistic production variability (Hu et al., 2025). Accordingly, the data source for this study can be defined as yield records collected from replicated field experiments on major legume species grown in representative ecological zones of Zhejiang, with each site-year combination treated as an independent environment. This structure makes it possible to separate average productivity from environmental sensitivity and provides the basic dataset needed for subsequent stability analysis.

The research materials should include several legume species with practical production relevance in Zhejiang, together with replicated observations from multiple environments. Existing legume stability studies typically use a randomized block or lattice design with three replications, which helps reduce field error and improves the reliability of yield comparisons (Habtegebriel and Abebe, 2023). Similar work in soybean has also used multi-location trials with elite lines and check cultivars across several environments, showing that replicated comparative testing is appropriate for identifying widely adapted and stable materials (Abebe et al., 2024). On this basis, the present study may use soybean, mung bean, adzuki bean, cowpea, and other locally important legumes as research materials, arranged in a uniform experimental design across test sites, with grain yield as the core trait and key agronomic characteristics recorded as auxiliary indicators.

3.2 Evaluation indicators

Yield stability should be evaluated from both productivity and response consistency, because high mean yield alone does not guarantee reliable adaptation across heterogeneous environments. Earlier soybean work showed that selection for yield alone often sacrifices some stability, while selection for stability alone may also reduce yield, so combined evaluation is more reasonable. Therefore, this study should first use mean yield as the primary performance index, and then combine it with classical stability statistics such as the coefficient of variation, regression coefficient, deviation from regression, Wricke's ecovalence, and Shukla's stability variance. These indices reflect different concepts of stability and can jointly describe whether a legume species performs consistently across favorable and unfavorable environments.

Recent studies indicate that no single stability parameter is sufficient for all breeding or agronomic decisions, so a composite indicator system is preferable. In lentil, significant positive relationships were reported among many parametric, non-parametric, and AMMI-based statistics, suggesting that several indices can be used together within the dynamic stability framework (Hossain et al., 2023). At the same time, some indicators behave differently because they emphasize distinct aspects of stability, and even the conventional coefficient of variation may require cautious interpretation when variance depends systematically on mean yield. For this reason, the present study can combine mean yield, CV, ASV, WAASB, and yield-stability ranking indices, so that both static consistency and high-yield adaptability are reflected in the final evaluation.

3.3 Data analysis methods

The statistical analysis should begin with combined analysis of variance, because ANOVA is the basic method for testing whether genotype or species effects, environmental effects, and their interactions are significant in multi-environment yield trials. When the interaction term is significant, further stability analysis becomes necessary, since changes in rank across environments mean that simple average yield cannot fully explain

adaptation differences. In practice, the analysis process may include tests of normality, calculation of environment-wise and pooled means, and partitioning of total variation into species, environment, and species-by-environment interaction components. This step provides the statistical basis for deciding whether the comparison of yield stability among legume species in Zhejiang is meaningful.

After ANOVA, the study should combine AMMI and GGE biplot analysis, because these two methods are widely used and complementary in interpreting genotype-by-environment interaction (Zhang et al., 2025). GGE biplot is especially useful for identifying winning genotypes, judging mean-versus-stability performance, and screening discriminating or representative test environments, while AMMI is more effective for decomposing interaction effects and deriving indicators such as ASV. To strengthen the robustness of conclusions, the results can further be compared with regression-based methods such as Eberhart-Russell analysis and with integrated ranking procedures such as WAASB, YSi, or average rank, because different methods may emphasize either responsiveness, static stability, or broad adaptation. In this way, the final methodological framework can achieve a more balanced evaluation of both yield level and yield stability among different legume species in Zhejiang. Overall, the data sources, evaluation indicators, and analytical methods for this study should all serve the same goal: comparing yield stability among different legume species in Zhejiang under realistic multi-environment conditions. A design centered on replicated field trials, multi-index stability evaluation, and combined ANOVA-AMMI-GGE analysis is well aligned with the research question.

4 Comparison of Yield Variation Characteristics among Different Legume Crops

4.1 Differences in long-term average yield among different legume crops

Across legume crops, long-term average yield differs substantially among species, and the basic pattern in the literature is that soybean usually ranks among the highest-yielding grain legumes, while some lupins or minor legumes remain clearly lower-yielding. In a direct species comparison, soybean averaged $3.99 \text{ t} \cdot \text{ha}^{-1}$ and had the highest seed yield among the tested legumes, whereas narrow-leafed and yellow lupin had the lowest yields. Long-term evidence from northern Europe also showed that narrow-leafed lupin yielded on average 11% more than faba bean and 25% more than pea, while faba bean still averaged 11% higher than pea, indicating that the ranking among non-soybean legumes can change by species and environment. For Zhejiang, this suggests that interspecific yield comparison should not assume a single universal order, but should distinguish between high-yielding species, moderate-yielding species, and species with lower but potentially more specialized adaptation (Figure 2).

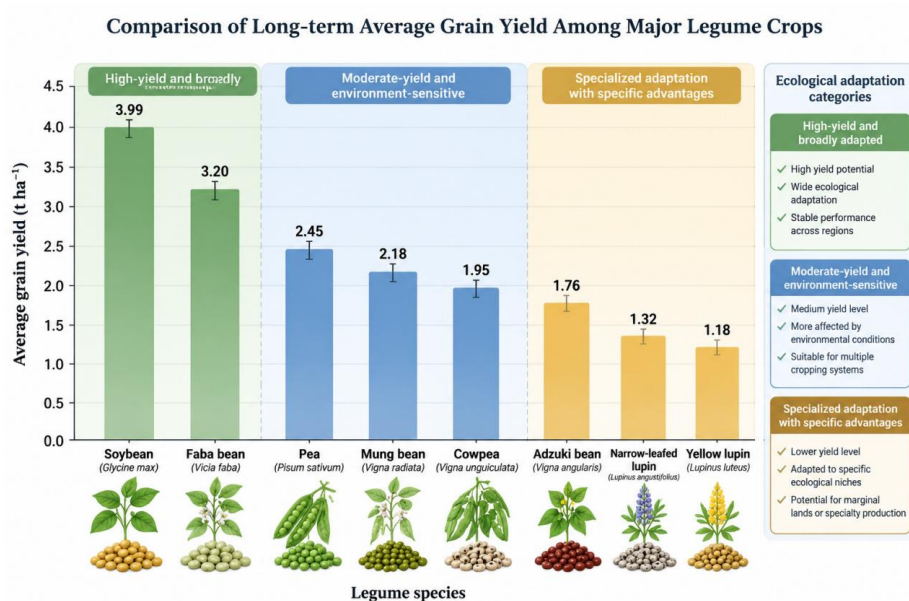


Figure 2 Comparison of long-term average yield performance among major legume crops and their ecological adaptation categories. The figure summarizes differences in yield potential and emphasizes that productivity ranking varies among species and environments

The differences in long-term average yield are also shaped by cropping system and management, rather than species identity alone. In southeast China, a nine-year rotation study found that kidney bean average yield under one rotation system was 7.47% higher than under another when recommended fertilization was used, showing that mean legume yield can shift markedly with system configuration. In another long-term subtropical rotation experiment, rice yield under a rice-faba bean sequence reached 8.73 t·ha⁻¹, 19.1% above the rice-wheat control, indicating that legume inclusion can raise the productivity of the whole system and indirectly alter the comparative value of different legume species within rotations (Yang et al., 2024). Therefore, when comparing average yields among legumes in Zhejiang, it is more appropriate to interpret observed species differences as the joint result of genetic potential, rotation fit, and management compatibility.

4.2 Annual variation trends

Annual yield variation is a core part of stability analysis because mean yield alone can mask large year-to-year fluctuations. A long-term experiment in southeast China showed that crop yield varied greatly over time under the influence of climate, precipitation, and other environmental factors, and that the yield trends of kidney bean and mustard differed significantly between rotation treatments over nine years (Zhang et al., 2022). Evidence from broader crop-yield analysis in China likewise showed that crop yields generally increased over time at the national scale, but with strong provincial differences in annual growth rates, indicating that temporal yield trajectories are rarely uniform across regions or crop types. Applied to Zhejiang legumes, this means annual variation should be evaluated not only by whether yield rises or falls, but also by the rate, direction, and consistency of change under different production environments.

Different legume crops also appear to differ in the magnitude of their interannual fluctuations. In species-comparison research, faba bean maintained relatively high yields but varied strongly among years, and one low-rainfall year caused a clear yield reduction, showing its sensitivity to annual weather anomalies (Jarecki and Migut, 2022). Broader evidence suggests that temporal instability in legumes is not necessarily extreme relative to other spring crops: across long-term European experiments, grain legumes showed 30% temporal instability, only slightly above spring cereals at 27%, and were judged as reliable as other spring-sown crops when assessed with scale-adjusted methods. For Zhejiang, annual yield trend analysis should therefore pay particular attention to whether specific legumes combine acceptable mean yield with limited fluctuation under variable rainfall, temperature, and seasonal light conditions.

4.3 Ecological-region performance

Yield performance across ecological regions differs because legume crops respond strongly to local climate, soil, and resource conditions. A large soybean dataset from China showed grain yield ranging from 1.4 to 4.5 t·ha⁻¹ across 146 locations, with the main climatic drivers shifting by region: temperature dominated in cool high-latitude areas, whereas radiation was more important in hot, humid low-latitude regions (Wu et al., 2023). Complementary evidence from explainable AI analysis across nine grain legumes found that different species respond differently to environmental factors, with cowpea showing higher productivity at elevated latitudes, while garden pea and faba bean were especially sensitive to soil moisture, organic matter, and soil type. This supports the expectation that legumes in Zhejiang will show clear regional differentiation between plains, coastal zones, and hilly uplands.

Regional comparison studies further show that legume-related yield outcomes often improve most in areas with stronger resource constraints or favorable hydrothermal conditions. A national meta-analysis found that legume green manure increased grain-crop yields in most regions of China, with the largest increase in Northeast China, and that benefits were greatest where annual precipitation exceeded 600 mm and annual mean temperature exceeded 10 °C (Liang et al., 2022). Similarly, a meta-analysis of soybean/maize intercropping concluded that the Yangtze River Basin was the most suitable region for adoption and that the system was especially beneficial in areas with limited agricultural resources. Since Zhejiang lies within the broader Yangtze River agricultural zone and has humid subtropical conditions, these results suggest that regional differences in yield performance among legume crops in the province are likely to reflect both ecological suitability and the extent to which each species

can exploit diversified, resource-efficient cropping systems. Overall, the available evidence supports comparing Zhejiang legume species through three linked dimensions: average yield level, annual fluctuation, and regional adaptation. This is the most appropriate basis for identifying legume crops that are not only productive, but also stable across Zhejiang's diverse ecological settings.

5 Comprehensive Evaluation of Yield Stability among Different Legume Crops

5.1 Stability comparison based on statistical indicators

Statistical indicators show that yield stability should be judged by combining mean performance with fluctuation measures rather than by yield alone. In soybean, high and stable yield is treated as the desired breeding target, but analyses also show that selecting only for yield can sacrifice stability, whereas selecting only for stability can reduce yield potential. For this reason, classical indicators such as the coefficient of variation, regression coefficient, deviation from regression, cultivar superiority, and rank-sum type indices are useful because they describe different aspects of adaptation and response consistency across environments.

At the same time, different indicators do not always rank materials in the same way, so their interpretation must be cautious. In lentil, several parametric and non-parametric statistics showed significant positive associations with mean yield, supporting the use of multiple indices under the dynamic stability concept (Hossain et al., 2023). By contrast, work on oat found that some commonly used statistics, including standard deviation, deviation from regression, Wricke's ecovalence, Shukla's variance, and AMMI stability value, tended to favor lower-yielding materials, while Pi, Bi, and YSI aligned better with yield improvement (Kebede et al., 2023). In addition, the traditional coefficient of variation can be misleading when variance depends systematically on mean yield, so adjusted forms of CV may provide a more defensible estimate of temporal stability.

5.2 Stability evaluation based on multi-model approaches

A more reliable comprehensive evaluation comes from multi-model analysis, especially the joint use of ANOVA, AMMI, GGE biplot, and integrated stability indices. In recent faba bean work, stability was assessed simultaneously through regression coefficient, deviation from regression, cultivar superiority, AMMI stability value, and genotype selection index, while AMMI and GGE were used to distinguish broadly adapted from specifically adapted genotypes (Wondaferew et al., 2024). Similar soybean studies also combined AMMI, GGE, WAASB, MTSI, and regression-based methods, showing that yield stability analysis is strongest when the same material is examined from several statistical perspectives rather than a single model alone (Habtegebriel and Abebe, 2023).

The value of this approach is that different models emphasize different dimensions of stability and can therefore complement one another. AMMI focuses on decomposing genotype-by-environment interaction and often identifies stable genotypes through low interaction scores, whereas GGE biplot is more useful for visualizing "which-won-where," ideal genotypes, and representative testing environments. Recent comparative analysis also showed that ASV, GGE, and GYT can produce slightly different rankings because one emphasizes interaction magnitude, another genotype-plus-interaction alignment, and another yield-trait balance, which means stability is inherently multidimensional. This interpretation is consistent with legume evidence from common bean, where AMMI, GGE, WAASB, and GSI identified overlapping but not identical stable genotypes and test environments (Estifanos et al., 2025).

5.3 Factors influencing yield stability

The main factors influencing yield stability are the environment, genotype-by-environment interaction, and the specific climatic and soil conditions that shape crop response. Across many legume trials, environment is often the largest source of variation: in field pea, environmental effects explained 59.62% of total variation and GEI explained 30.11%. In faba bean grown across different regions, the environment explained 81-93% of variation for most traits, while genotype contributed much less for many characteristics (Papastylianou et al., 2021). This means that differences in rainfall, temperature, season, and location are likely to dominate yield fluctuation among legume crops in Zhejiang.

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

biomass nitrogen, and nodule number (Luo et al., 2024). Root interaction studies also showed that closer interspecific contact can intensify symbiotic nitrogen fixation, promote nitrogen assimilation and amino-acid export, and ultimately raise nitrogen-use efficiency and yield in intercropped pea. For Zhejiang, these results suggest that stable legume yields are more likely where species possess efficient nodulation, strong root plasticity, and compatibility with diversified cropping systems that improve belowground ecological function.

6.3 Genetic characteristics and genotype-environment interactions

The genetic basis of yield stability in legumes is inseparable from genotype-environment interaction, because the same genotype can perform very differently across locations, years, and management conditions. In faba bean, yield instability is explicitly attributed to GEI, and large interaction effects reduce heritability and weaken the correspondence between phenotypic performance and genetic value, making selection progress slower (Sokolović et al., 2025). Similar evidence from chickpea shows that stability breeding must distinguish between static stability, where performance changes little across environments, and dynamic stability, where genotypes respond predictably while maintaining high productivity (Eskezia et al., 2025). This implies that legume yield stability in Zhejiang should be interpreted not as simple invariance, but as the ability of a species or genotype to maintain relatively high yield under environmental fluctuation without excessive rank reversal.

A second mechanism is the presence of usable genetic diversity for adaptive traits, together with analytical tools that identify broadly or specifically adapted materials. Studies in faba bean show that stable variety development depends on substantial genetic variation, because this diversity provides the basis for selecting cultivars suited to local climate, altitude, and soil conditions. At the same time, crossover interactions can shift genotype rankings across yield environments, so identifying where these crossovers occur helps separate narrowly adapted from broadly adapted materials and avoids yield penalties from poor genotype choice. Breeding for stable legume production therefore requires combining diverse germplasm, multi-environment testing, and methods such as GGE, AMMI, or multi-trait stability indices to match genotypes to the ecological heterogeneity typical of Zhejiang. Overall, yield stability formation in legumes depends on three linked mechanisms: climate adaptation under compound stress, efficient physiological-ecological support for nitrogen and biomass production, and genetic adaptation shaped by genotype-environment interaction. These mechanisms jointly determine whether a legume species can sustain reliable yield across Zhejiang's diverse environments.

7 Case Study: Yield Stability Analysis of Legume Crops in Typical Ecological Regions of Zhejiang Province

7.1 Selection of study regions and research design

The case study regions should be selected to represent the main ecological contrasts that shape legume production in Zhejiang, such as plains, river-valley basins, coastal areas, and hilly uplands. Multi-environment trials are the standard design for evaluating adaptation and stability across heterogeneous conditions, because they allow the same crop materials to be compared under differing temperature, rainfall, soil, and management backgrounds. Experience from Chinese pea trials further shows that broad climatic coverage across locations and years is necessary for identifying both widely adapted and specifically adapted materials, rather than assuming that one genotype or species performs uniformly everywhere.

Accordingly, the research design for Zhejiang can be organized around several representative county-level sites, with each site-year combination treated as an independent environment and each legume species tested under a unified field protocol. Similar legume studies commonly use randomized complete block or lattice designs with three to four replications, which improves the precision of yield comparison under variable field conditions (Haile and Tesfaye, 2024). Case studies from other ecological regions also show that dividing production areas into mega-environments helps identify groups of locations with similar crop responses, making regional interpretation more meaningful than using provincial averages alone (Figure 3).

7.2 Yield stability performance

In the case study regions, the first expectation is that different legume crops will show clear differences in both mean yield and stability because genotype, environment, and their interaction usually all contribute significantly

to grain-yield variation. This pattern has been observed in soybean multi-location trials, where grain yield ranged from 979.8 to 3645 kg·ha⁻¹ and significant differences were detected among genotypes, environments, and GEI. Comparable results were reported for common bean, where AMMI analysis confirmed that grain yield changed significantly across environments and supported the identification of both broadly adapted and specifically adapted genotypes (Daemo, 2024).

Agro-ecological Zoning and Multi-environment Trial Sites for Legume Yield Stability Evaluation in Zhejiang Province, China

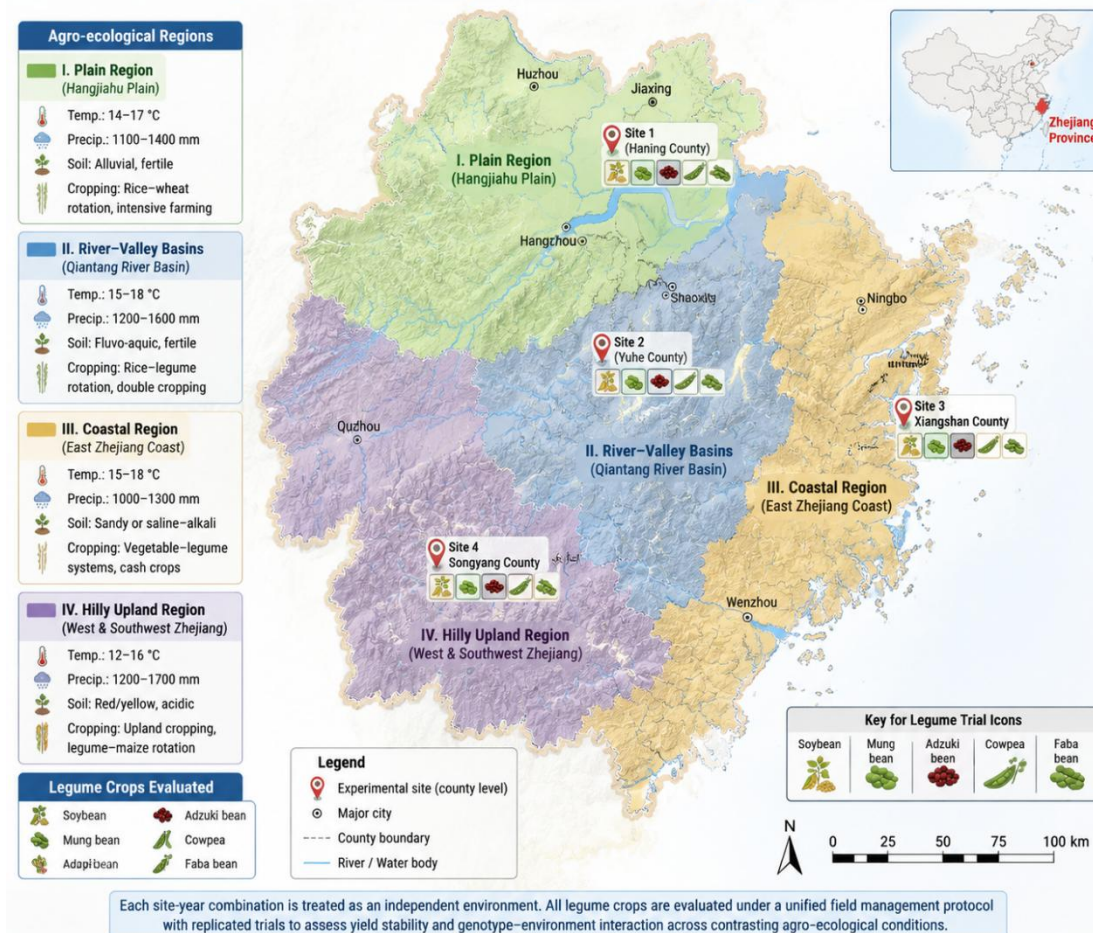


Figure 3 Agro-ecological zoning and representative multi-environment trial locations for evaluating legume yield stability across Zhejiang Province, China. The map highlights contrasting production environments including plains, river valleys, coastal zones, and hilly uplands

A second likely pattern is that some legume crops or varieties will be broadly adaptable across Zhejiang, while others will perform best only in certain ecological zones. In faba bean, GGE biplot analysis identified genotypes with low GEI and broad adaptability, showing that materials less affected by environmental fluctuation are more reliable across diverse sites (Wondaferew et al., 2024). In southern China pea trials, the tested environments were partitioned into two mega-environments, and some genotypes were stable across many sites while others showed clear specific adaptability to particular environments. For Zhejiang, this implies that soybean or mung bean may perform more steadily across multiple regions, whereas adzuki bean, cowpea, or pea may express stronger ecological specialization depending on thermal and moisture conditions.

7.3 Implications and optimization

The main implication of the Zhejiang case study is that production recommendations should be based on region-specific matching of crop type and ecological setting, rather than on a single provincial ranking of legume crops. Work from other Chinese ecological regions shows that the best-performing legume mixtures differed among locations, and the recommended crop combinations were therefore region-specific rather than universal

(Luo et al., 2023). More broadly, identifying representative test environments is valuable because selection in those environments can improve the efficiency of screening and strengthen recommendations for similar agro-ecological conditions.

Production optimization should therefore combine species selection with cropping-system adjustment and soil management. Legume-based rotations tend to maintain yields and production stability by improving soil fertility and reducing dependence on external inputs. Long-term evidence from China also shows that legume inclusion can support more stable subsequent crop production and greater resistance and resilience under changing fertilization conditions, indicating that stability benefits are not limited to a single season (Liu et al., 2023). In practical terms, Zhejiang should prioritize legume species with broad adaptation for large-scale promotion, reserve specifically adapted species for matching ecological niches, and integrate legumes into rotations or intercropping where soil quality, resource-use efficiency, and system-level stability can all be improved. Overall, this case-study framework supports a comparative and regionally differentiated interpretation of yield stability among legume crops in Zhejiang. It is most useful for identifying which legumes are broadly stable, which are locally advantageous, and how production can be optimized through ecological matching and diversified cropping systems.

9 Conclusions and Future Perspectives

This study conducted a systematic comparison of yield stability among major legume species cultivated across Zhejiang Province, drawing on multi-year, multi-location data to capture the full spectrum of environmental variability characteristic of the region. The results reveal that soybean and broad bean exhibit relatively high yield stability, with lower coefficients of variation across years and ecological zones, while cowpea and adzuki bean display greater interannual fluctuation. These differences are attributable to a combination of physiological traits, root system architecture, and sensitivity to temperature and precipitation extremes during critical growth stages. A second key finding is that genotype-environment interaction effects are pronounced for all legume species examined, meaning that a variety performing well in one ecological subregion of Zhejiang may underperform in another. The application of multiple stability parameters-including the coefficient of variation, Shukla's stability variance, and AMMI-based stability scores-demonstrated that no single indicator fully captures the complexity of yield stability, and a composite evaluation framework is essential for robust ranking. Taken together, the findings provide an evidence base for tailoring legume variety selection and cropping system design to specific agro-ecological conditions within the province.

Several limitations should be acknowledged. First, the temporal coverage of the yield data, while spanning multiple years, may not fully capture the increasing frequency of extreme weather events associated with ongoing climate change, potentially limiting the predictive value of historical stability estimates. Second, the analysis relied primarily on regional aggregate statistics and published trial records; farm-level heterogeneity in management practices, soil fertility, and pest pressure could not be fully controlled, introducing unquantified variability into the stability comparisons. Third, the study focused on the most widely planted legume species and did not include minor or underutilized legumes that may hold untapped resilience potential. Future research should prioritize several directions. Long-term, standardized field experiments across representative ecological zones of Zhejiang are needed to generate high-resolution, plot-level yield data under controlled management protocols. Integrating crop growth models with climate projection scenarios would allow researchers to simulate yield stability under future warming and altered precipitation patterns, providing forward-looking guidance rather than retrospective description. Additionally, genomic and molecular tools-including marker-assisted selection and genome-wide association studies-should be leveraged to identify quantitative trait loci associated with stability-related traits, accelerating the breeding of climate-resilient legume varieties. Finally, socio-economic dimensions such as farmer adoption behavior, market price volatility, and the profitability of stable versus high-yielding varieties warrant investigation to ensure that agronomic recommendations are economically viable.

The legume industry in Zhejiang Province holds considerable development potential, driven by growing consumer demand for plant-based protein, the ecological benefits of legumes in crop rotation systems, and policy support for

sustainable agriculture. Strengthening the breeding and extension of stable-yielding, climate-adapted varieties tailored to the province's diverse ecological subregions is a strategic priority. Precision cultivation technologies-including drip irrigation, sensor-based nutrient management, and mechanized planting and harvesting-can further reduce yield variability and improve resource-use efficiency, particularly in the face of labor shortages and rising input costs. Looking ahead, the integration of legume production into broader sustainable cropping systems offers a pathway to enhance soil health, reduce nitrogen fertilizer dependency, and improve the resilience of the entire agricultural landscape. Policy incentives that encourage legume inclusion in rice-based rotations, coupled with the development of regional legume brands and value-added processing chains, could simultaneously raise farmer incomes and strengthen domestic protein supply. Collaborative networks among research institutions, extension services, and producer cooperatives will be essential to translate stability research into practical, scalable improvements across the province's legume sector.

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Conflict of Interest Disclosure

The author affirms 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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