is often smaller than the apparent number of parents. As a result, offspring populations are prone to founder effects and genetic drift, leading to rapid loss of rare alleles. Notably, such genetic erosion may not immediately manifest as a significant decline in heterozygosity but is often first reflected in reduced allelic richness and imbalanced family contributions. Therefore, relying on a single indicator to evaluate the genetic quality of cultured populations may underestimate potential risks. Moreover, directional selection for traits such as growth rate, feed efficiency, and disease resistance may lead to selective sweeps in specific genomic regions, forming distinct patterns of population differentiation (Wu et al., 2024). Without proper pedigree records and parentage verification, repeated use of closely related broodstock can exacerbate inbreeding and relatedness accumulation. Thus, molecular marker-based parentage analysis, pedigree reconstruction, and family contribution assessment are crucial for maintaining stable genetic structure in cultured populations (Weng et al., 2021).

### 3.3 Relationship between genetic diversity and germplasm improvement

Genetic diversity is the foundation of germplasm improvement and genetic breeding. Abundant genetic variation provides the necessary basis for selecting desirable traits, estimating genetic parameters, and improving breeding values. In grouper breeding, whether through traditional mass selection, family-based selection, marker-assisted selection, or genomic selection, all approaches fundamentally rely on the available genetic variation within populations. If genetic diversity is insufficient, the reservoir of favorable alleles and opportunities for recombination are limited, leading to reduced breeding response and even stagnation in long-term improvement (Houston et al., 2020; Hsu et al., 2023; Wu et al., 2024). This is particularly important for complex economic traits such as growth rate, feed efficiency, disease resistance, and environmental tolerance, which are typically controlled by multiple genes. Sustained genetic gain can only be achieved when the base population maintains sufficient genetic variation.

On the other hand, genetic diversity assessment provides direct guidance for broodstock management and breeding population design. Using microsatellite and SNP markers for pedigree reconstruction, parentage identification, and kinship analysis enables accurate evaluation of parental contributions, control of inbreeding accumulation, balancing of family representation, and optimization of hybrid combinations (Weng et al., 2021). For aquaculture species like groupers, which rely heavily on artificial propagation and hatchery expansion, the absence of molecular-level pedigree management can result in repeated use of a few core broodstock, reducing effective population size and weakening the breeding foundation. In hybrid breeding, an appropriate level of genetic divergence is also a prerequisite for heterosis. If parental genetic backgrounds are too similar, heterosis may be limited; if the genetic distance is too large, risks such as unstable combining ability, developmental abnormalities, and increased segregation in offspring may arise (Xu et al., 2025). Therefore, genetic diversity analysis not only aids in broodstock selection but also helps establish theoretical relationships between genetic divergence and hybrid performance.

Furthermore, genetic diversity assessment provides important support for wild resource conservation and the renewal of cultured germplasm. By comparing genetic differences between wild and cultured populations, it is possible to identify whether genetic diversity loss, pedigree admixture, or localized genetic degeneration has occurred in aquaculture systems, thereby informing decisions on introducing wild germplasm or restoring local populations (Weng et al., 2021; Yang et al., 2022; Chen et al., 2025). At a broader scale, studies of population structure and historical dynamics help define management units, protect key spawning populations, and conserve unique genetic lineages—factors that are critical not only for natural resource conservation but also for maintaining a sufficiently broad genetic base for future breeding systems (Vaini et al., 2021). Therefore, grouper germplasm improvement must adhere to the principle of balancing “conservation and utilization”: on the one hand, maintaining sources of variation by increasing effective population size, introducing new germplasm, and preserving clear genetic structure; on the other hand, improving selection efficiency through molecular markers, whole-genome information, and trait association analyses. Only by advancing germplasm improvement on the premise of preserving genetic diversity can the grouper aquaculture industry achieve sustainable, stable, and high-quality development.