

lipid-centered pathways and high-protein genotypes activated nitrogen-centered pathways, whereas proteomic comparison of two contrasting varieties indicated that compositional differences were driven mainly by the peripheral proteome, which changed strongly across developmental stages (Huang et al., 2025; Niu et al., 2025). Importantly, this trade-off is not absolute in all materials: under heat and drought stress, several high-protein lines maintained 46%-55% protein, and two lines showed no apparent negative relationship between seed protein and oil contents, indicating that some varieties partially escape the usual antagonism between these traits (Figure 2) (Kakati et al., 2024).

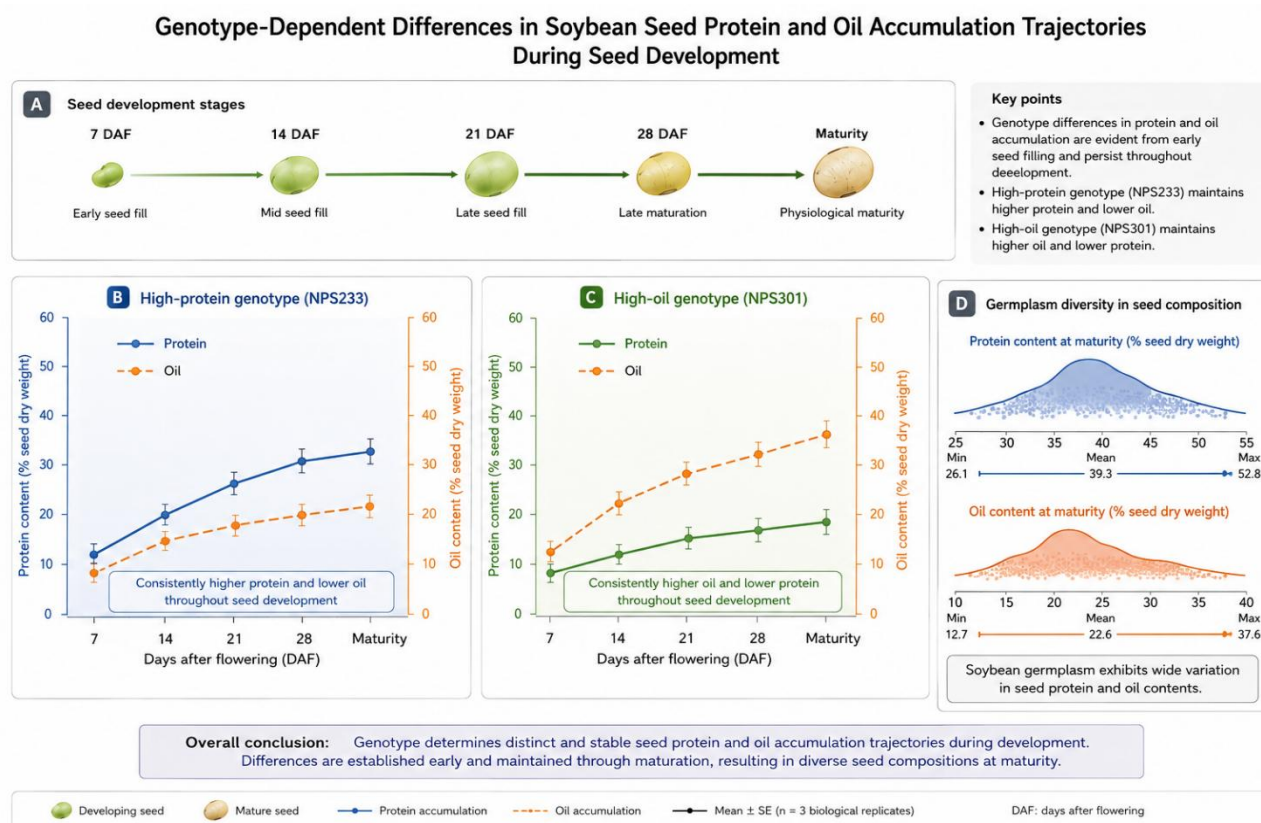


Figure 2 Developmental trajectories of seed protein and oil accumulation in contrasting soybean genotypes

6.2 Effects of environmental stress on seed composition dynamics: a case study

Environmental stress alters the rate and balance of storage compound accumulation, but the direction and magnitude of change depend on the stress scenario and genotype. A meta-analysis found that water stress reduced the absolute accumulation of protein, oil, and residual fractions per seed, yet protein was less affected than oil, which increased final protein concentration on a dry-weight basis; similarly, controlled experiments showed that severe drought increased protein by 4.4 percentage points and decreased oil by 2.9 percentage points during seed fill. Temperature acts in a comparable but not identical way, because high temperature also tends to raise protein concentration without increasing protein synthesis per se, indicating that stress often changes composition through differential suppression of reserve classes rather than through direct stimulation of protein deposition.

Case studies across multiple environments show that these responses are strongly modified by genotype × environment interaction. In Croatia, 32 elite genotypes grown across six dry and eight normal environments showed significant effects of genotype, environment, and their interaction for both traits; drought decreased mean protein by 4.5% and slightly increased oil by 1.2%, and the usual negative protein-oil correlation seen in normal environments disappeared under dry conditions. At larger scale, U.S. synthesis-analysis showed that environment accounted for more than 70% of the variation in seed composition, while management-induced environmental shifts such as delayed planting reduced oil concentration, reinforcing that stress effects on accumulation dynamics emerge from the combined action of weather, timing, and genotype rather than from a single factor alone.