

advanced the timing of maximum oil concentration, and increased the rate of late-stage protein accumulation, whereas low temperature prolonged seed growth but reduced growth rate, demonstrating that climate alters both the rate and timing of reserve deposition.

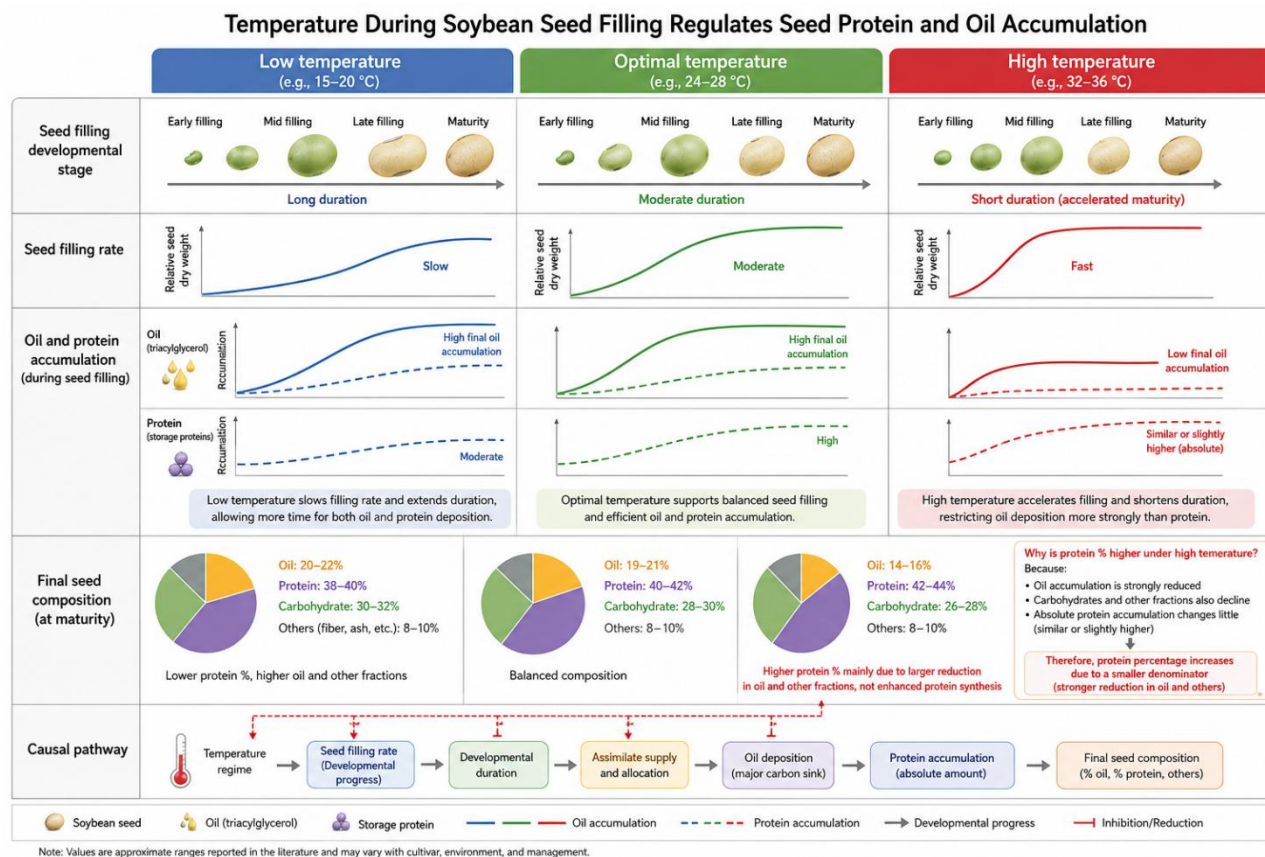


Figure 1 Conceptual framework illustrating the effects of temperature during soybean seed filling on protein and oil accumulation

4.2 Effects of water availability and drought stress

Water limitation during seed development alters both final composition and the temporal pattern of reserve accumulation, but its effect depends strongly on the developmental stage at which stress occurs. A broad meta-analysis found that water stress reduced the absolute content of protein, oil, and residual fractions per seed, yet protein accumulation was less affected than oil accumulation, leading to a higher final protein concentration on a dry-weight basis (Mo et al., 2024). Complementing this general result, mechanistic work showed that drought can change both the rates and durations of component accumulation while maintaining overall seed growth rate, with compensation typically favoring protein because late seed filling can rely more on remobilizable nitrogen whereas oil synthesis depends more heavily on current photosynthesis.

Field studies show that reproductive-stage drought is particularly important for soybean quality because it shifts partitioning away from oil and toward protein while simultaneously reducing yield. In Brazil, water deficit imposed during the reproductive stage consistently produced higher protein and lower oil contents across genotypes, whereas vegetative-stage stress had much weaker compositional effects. However, drought does not act independently of temperature: analyses from Argentine multi-environment trials showed that under stronger water deficit, oil concentration increased with increasing mean temperature whereas protein still increased with temperature but decreased with water deficit, underscoring that climate effects on seed composition should be interpreted as joint heat-water responses rather than isolated factors.

4.3 Effects of nutrient management and cultivation practices

Among agronomic factors, nutrient supply-especially nitrogen-has the most consistent documented effect on seed composition, because nitrogen availability during seed filling directly constrains protein deposition. Across a large