steaming and drying, simmering, and the well-known "nine-steam-nine-bask" process, while innovative approaches such as constant temperature and humidity steaming combined with vacuum-steam pulsed steaming have shown superior outcomes. The constant temperature and humidity combined with vacuum-steam pulsed steaming and drying method yielded the highest antioxidant capacity, better preservation of polysaccharides, and lower levels of 5-hydroxymethylfurfural compared to traditional atmospheric steaming. This innovative method also reduced production time by 66.7% while achieving a comparable color profile to conventional technology (Ren et al., 2025).



Figure 1 The *P. cyrtonema* rhizome samples during nine processing cycles of steaming and drying (Adopted from Shen et al., 2024)
Image caption: CP represents the crude rhizome samples and SD3, SD6, and SD9 represent the processed samples subjected to three, six, and nine processing cycles, respectively (Adopted from Shen et al., 2024)

Processing methods and cycle numbers profoundly affect chemical composition, with strong consensus that excessive steaming leads to over-processing. Total polysaccharide content decreases progressively with increasing processing cycles, stabilizing at approximately 5.2 g/100 g after four cycles, a 45.81% reduction from raw rhizomes (Yao et al., 2022). In *Polygonatum sibiricum*, polysaccharide content decreased by 47.38% after nine cycles, with the most significant decline occurring in the first three cycles. Low molecular weight fructans underwent significant degradation within the first three processing cycles, with complete degradation by the seventh cycle, suggesting that the traditional nine-cycle method may be excessive (Mei et al., 2025). Total saccharides in *P. cyrtonema* increased from one to four cycles but decreased from four to nine cycles, indicating that four cycles of steam-heated air drying represents the ideal processing method for optimal saccharide, fructose, and phospholipid retention (Zhu et al., 2022).

Different thermal processing methods, steaming, wine-processing, and processing with auxiliary materials such as black beans, produce distinct chemical transformations. Wine-processed *P. cyrtonema* exhibited the best comprehensive quality, with surface colors gradually deepening, sweetness increasing, viscosity strengthening, and tongue-numbing sensation disappearing after processing. Steaming *Polygonatum kingianum* with black beans promoted a dual metabolic enhancement, incorporating isoflavones and triterpenoid saponins from black beans while most active components peaked after three steaming cycles. Multiple steaming and roasting methods increased sugars, nucleotides, esters, and flavonoids but reduced amino acid content significantly, with sugars predominantly being monosaccharides from polysaccharide depolymerization (Xu et al., 2023). Processing-induced chemical mechanisms include hydrolysis, oxidative decomposition, dehydration, Maillard reaction, and polymerization, with Maillard reactions between amino acids and reducing sugars being the primary driver of browning (Jiang et al., 2022).

3.3 Drying, shaping, and storage management

Drying methods significantly affect the final quality of processed *Polygonatum*, with different techniques offering distinct advantages and limitations. Among five drying methods-hot-air drying, infrared drying, microwave drying, freeze-drying, and vacuum drying, vacuum drying achieved an optimal balance between energy consumption and product quality, demonstrating significant advantages in maintaining antioxidant activity, active ingredients, and flavor. Microwave drying achieved the highest drying rate with a drying time only 1/83 that of freeze-drying, yet demonstrated a relatively low retention rate of total polysaccharides. Freeze-drying maintained antioxidant activity and active ingredients effectively but required extended duration of 1 080 minutes, leading to high energy