consumption that restricts large-scale industrial application (Wang, 2026). Heated-air drying and infrared drying were not suitable replacements for traditional steam-sun drying, as hierarchical cluster analysis showed these methods produced samples far in distance from steamed ones (Zhu et al., 2022).

Drying parameters, including temperature, time, and steaming cycles, must be carefully controlled to optimize quality and minimize harmful byproduct formation. Response surface methodology and back-propagation neural network optimization of wine-processed *P. sibiricum* identified optimal conditions of 3.6 hours steaming time, 75℃ drying temperature, 11.4 hours drying time, and eight steaming cycles, which improved taste and bioactivity while reducing 5-hydroxymethylfurfural to 0.18 mg/g. Polysaccharides undergo hydrolysis under moist heat during drying, resulting in continuous accumulation of reducing sugars that promotes 5-HMF formation, making drying temperature and time critical control points (Li et al., 2026). For laboratory analysis, processed samples were ground and passed through a 40-mesh sieve and the resulting powder stored in a desiccator; these are analytical preparation procedures rather than general commercial storage specifications (Mei et al., 2025). The lack of precise control of processing parameters has led to uneven quality of processed *Polygonatum*, underscoring the need for standardized drying and storage protocols to ensure consistent product quality (Bi et al., 2025).

## 4 Effects of Primary Processing on the Formation of Commercial Specifications of *Polygonatum*

### 4.1 Changes in rhizome size, integrity, and external morphology

Thermal processing induces significant structural degradation in *Polygonatum* rhizomes, disrupting the microscopic pore wall structure and facilitating the release of intracellular components. Repeated steaming and drying cycles cause the rhizome surface to become wrinkled and shriveled as moisture is lost and cellular matrices collapse. Initial processing effectively disrupts cell wall structure, leading to a slight increase in extracted crude polysaccharide yields, though yields stabilize with further processing cycles as the enhancement effect reaches its limit (Mei et al., 2025). The disintegration of calcium oxalate raphides, which cause throat irritation, is a primary morphological goal of processing, with the change rate of needle crystals exceeding 90% by the fifth processing cycle (Cheng et al., 2022).

Raw material dimensions significantly influence post-processing morphology and final product integrity. Among different lengths of *Polygonatum cyrtonema*, short-length rhizomes with younger tissues demonstrated better performance after processing, indicating that preliminary sorting by size and maturity preserves structural integrity. Slice thickness dictates drying kinetics, as moisture diffuses from the interior to the exterior during hot-blast air drying, with steamed samples of less than 6 mm thickness exhibiting faster water loss and superior quality retention (Liu et al., 2022). The physical breakdown of rhizome tissue during steaming also enhances the solubility and dissolution rates of chemical components, which subsequently increases extract yields in the processed material.

### 4.2 Changes in color, texture, and processing yield

Color transformation is a primary visual indicator of processing adequacy and commercial quality in *Polygonatum*. The inner transverse section of processed rhizomes gradually turns moist black with a specular luster, matching the traditional identification standard of "brightness like oil and color like black lacquer". Quantitative colorimetric analysis using the CIE L*a*b* color space demonstrates that L* values significantly decrease while ΔE*ab values increase from crude to steamed to wine-processed products, reflecting the progressive darkening of the rhizome surface (Figure 2) (Cheng et al., 2022). In *Polygonatum sibiricum*, optimal quality corresponds to an L* value ranging from 21.0 to 22.0 and an a* value between 2.0 and 5.0, establishing specific chromatic thresholds for commercial grading. The browning mechanism is primarily driven by non-enzymatic Maillard reactions between amino acids and reducing sugars, alongside caramelization and the oxidative polymerization of phenolic substances (Ren et al., 2025).