Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.35205

Tracing the geographical origin of ginger (*Zingiber officinale* Roscoe) using multi-isotope fingerprints from South Korea and China

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This study evaluates the effectiveness of stable isotope analysis (C, N, H, and O) in distinguishing the geographical origin of fresh ginger (*Zingiber officinale* Roscoe) cultivated in South Korea and China (Shandong and Yunnan). A total of 12 Korean and 24 Chinese samples were analyzed. Overall, South Korean ginger exhibited higher $\delta^{15}N$ and $\delta^{2}H$ values compared to Chinese ginger. In particular, the $\delta^{2}H$ values in Yunnan ginger from China were as low as −85‰, while the $\delta^{18}O$ values were significantly higher in South Korean ginger.

The ginger samples were analyzed using multivariate statistical methods, including Principal Component Analysis (PCA), Partial Least Squares Discriminant Analysis (PLS-DA), Linear Discriminant Analysis (LDA), Random Forest, and one-way Analysis of Variance (ANOVA). In PCA, the first two principal components explained 76.4% of the total variance and separated the Yunnan group, although considerable overlap remained between the South Korean and Shandong groups. The PLS-DA model yielded an overall classification accuracy of 77.8%. The model demonstrated strong performance for the Yunnan group (91.7% accuracy), while misclassifications occurred between the South Korean and Shandong groups, consistent with the PCA results. In contrast, supervised learning models, including LDA and Random Forest, demonstrated improved discrimination of all three geographical groups. One-way ANOVA further confirmed that $\delta^{18}O$ significantly differentiated all three groups ($p < 0.01$), while $\delta^{15}N$ and $\delta^{2}H$ primarily distinguished the South Korean and Yunnan samples, respectively. South Korean ginger exhibited significantly higher $\delta^{15}N$ and $\delta^{18}O$ values compared to both Chinese counterparts. Variable importance analysis using the Random Forest model identified $\delta^{2}H$ and $\delta^{18}O$ as the most influential predictors for origin discrimination. These isotopic differences likely reflect regional variations in precipitation isotopic compositions, climatic conditions, and agricultural nitrogen inputs, demonstrating how environmental and biogeochemical processes are recorded in plant tissues. Overall, the integration of multi-isotope profiling with statistical modeling provides a robust framework for geographical origin authentication of ginger.