Development of a Rapid and Cost-Effective Lipidomic Analysis for Milk and Dairy Products via Raman Spectroscopy

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Abstract

Milk fat is a primary component of milk, contributing significantly to flavor, nutritional value, and technological properties. Its fatty acid profile is highly sensitive to physiological, microbial, and environmental shifts, potentially serving as a biomarker for the cow's metabolic state and an indicator of milk quality post-milking. Despite its importance, standard tools for assessing changes in milk fat are generally based on complex chemical methods and lengthy procedures that are not always suitable for routine application. Consequently, there is an increasing need to develop rapid, non-destructive analytical approaches for the direct characterization of fat composition and the detection of structural changes. The aim of this research was to evaluate the use of Raman spectroscopy as a non-invasive analytical technology to characterize alterations in the fatty acid composition and lipid structure of milk. To this end, experiments were conducted to demonstrate how various conditions, including oxidative processes, microbial inoculation, and improper storage, are reflected in the Gas Chromatography (GC) fatty acid profile and the Raman spectrum. Oxidative treatments showed a clear emergence of Raman spectral markers, which correlated with shifts in the fatty acid profile measured by GC, potentially indicating oxidative degradation. Microbial inoculation resulted in distinct differences in fatty acid composition, as evidenced by shifts in spectral intensities and peak positions. Furthermore, improper storage conditions led to substantial chemical alterations. Notably, repeated freeze-thaw cycles, which did not result in detectable chemical changes via GC, led to significant variations in the Raman scattering patterns. These findings suggest that Raman spectroscopy can serve as a sensitive, non-invasive, and complementary tool for identifying changes in the fatty acid composition and lipid structure of milk. This capability enables the monitoring of processes such as oxidation, microbial contamination, or improper storage, highlighting the potential for applying this approach in quality monitoring and industrial process control.