

Highlights of Analytical Sciences in Switzerland

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Analytical Mapping Reveals the Inherent Heterogeneity of Swiss Hard Cheese

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Swiss hard cheeses, such as Gruyère and Emmentaler, are fermented products whose quality is largely defined by their aroma. In Switzerland, a common procedure is the evaluation of the cheese's market value by degustation of one core sample, implicitly assuming that a cheese loaf represents a homogeneous unit. To address this assumption, we developed 3D sampling designs (Figs. 1 a and b) to evaluate the distribution of volatile organic compounds (VOCs), microbiota, physicochemical parameters, and sensory attributes, from the rind to the core. VOCs were analysed using vacuum in-tube extraction coupled to gas chromatography mass spectrometry (V-ITEX-GC-MS), while microbial communities were characterised by 16S rRNA amplicon sequencing. These datasets were complemented by measurements of pH and NaCl concentration, as well as trained sensory evaluations.

The results revealed pronounced heterogeneity within the cheese loaf. VOCs were unevenly distributed, with sulfur compounds, esters, and pyrazines predominantly located in the outer zones, while lactones, aldehydes, and ketones were more abundant in the core. Beyond outer-inner differences, several compound classes exhibited localised hotspots, as illustrated by the representative sulfur compound distributions in Fig. 1d. These analytical gradients were consistently reflected in the sensory profiles, with the outer zones showing more intense, complex, and pungent attributes, while inner regions were characterised by

milder, dairy-like and nutty notes. This relationship is exemplarily shown for the distribution of sulfur compounds and sulfur aroma in Fig. 1c and Fig. 1d. This indicates that aroma formation is influenced by spatially confined biochemical and microbial processes rather than uniform diffusion alone.

Different lactic acid bacteria showed zone-specific dominance along gradients in pH and NaCl concentration (exemplarily shown for NaCl and *Streptococcus thermophilus* in Fig. 1c), suggesting a correlation between physicochemical conditions and microbial presence reported in previous studies, potentially linked to differences in oxygen availability, salt tolerance, and acidification dynamics. While these microbial distribution patterns are consistent with the variability observed in VOC profiles, direct attribution of individual compounds to specific microorganisms is often not possible. Bringing these observations together, the multifactor analysis biplot (Fig. 1e) integrates chemical, microbial, physicochemical, and sensory parameters, revealing their combined contribution to the heterogeneous organisation of the cheese.

Our study highlights the importance of adapting sampling strategies to the inherent heterogeneity of cheese loaves, as both analytical characterisation and quality grading based on single-point sampling risk incomplete representation of the cheese. This heterogeneity also provides a plausible explanation for why different portions taken from the same cheese can exhibit distinct sensory characteristics, and why consumer preferences may vary between the inner paste and the outer zones close to the rind.

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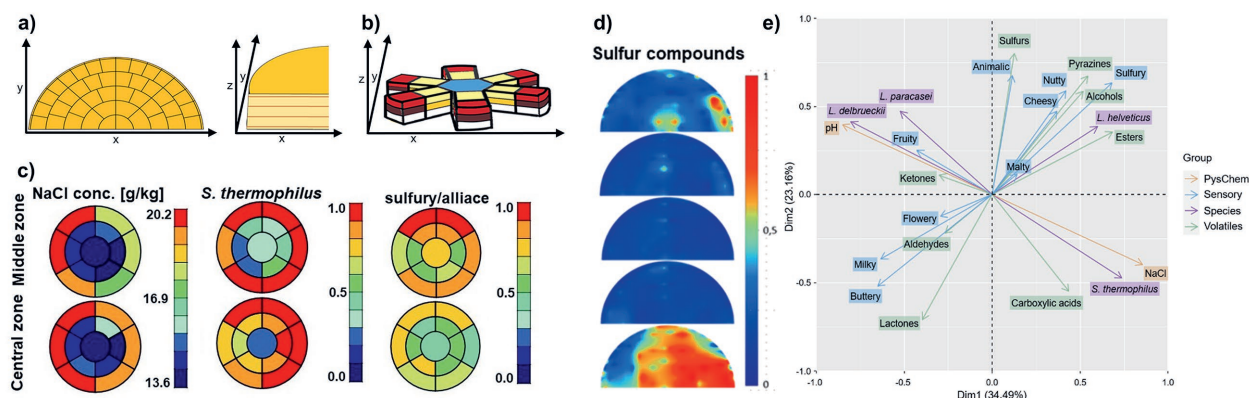


Fig. 1. (a, b) Schematic representation of the three-dimensional sampling strategies applied to the cheese loaf. (c) Spatial distribution of NaCl concentration, *Streptococcus thermophilus*, and sulfury/alliaceous sensory intensity. (d) Representative distribution of sulfur compounds. (e) Multifactor analysis (MFA) biplot integrating physicochemical, microbial, volatile, and sensory parameters.

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