

Spoilage Detection in Aging Paneer: Development of Non-destructive Sensing Technology and Microbiome Characterization

ABSTRACT

Paneer is a high-moisture, high-protein fresh cheese with a short, refrigerated shelf life, resulting in rapid spoilage, economic losses and potential safety risks. Conventional quality assessments, such as aerobic plate count, are destructive, time-consuming and laboratory-dependent, while existing non-destructive methods are often costly. This thesis aimed to develop a rapid, non-destructive freshness indicator for paneer by integrating biochemical and microbiological changes, microbial community dynamics, kinetic modelling and dielectric properties through a capacitance-based sensor.

Paneer prepared from a 50:50 cow and buffalo milk blend was stored at 0, 4 and 7 °C for 21 days, with sampling at three-day intervals. Moisture, pH, titratable acidity, aerobic plate count (APC), fatty acid profile, particularly oleic acid (C18:1), and casein content were analysed following FSSAI protocols. Microbial communities in samples stored at 4 °C were characterised using 16S rRNA and ITS amplicon sequencing. Zero-, first- and nth-order, modified Gompertz and Arrhenius models were evaluated for spoilage kinetics. A parallel-plate capacitance sensor integrated with an LC oscillator operating at 70 and 50 kHz was developed to monitor spoilage-related frequency changes.

Moisture, pH and casein decreased, whereas acidity and APC increased during storage. The FSSAI APC limit (3.5×10^5 CFU/g) was exceeded by days 18, 12 and 6 at 0, 4 and 7 °C, respectively, with Q_{10} values of 2.1–2.8. Lipolysis was evident from changes in fatty acids, with oleic acid decreasing from 29.8% to 11.5% by day 21 at 4 °C. Microbial succession shifted from predominantly lactic acid bacteria (88%) in fresh paneer to psychrotrophic genera, including *Pseudomonas*, *Acinetobacter* and *Enterobacter* (68%), during advanced spoilage. PICRUSt analysis indicated enrichment of lipid, amino acid and proteolysis-related pathways.

First-order kinetics best described oleic acid degradation ($R^2=0.962$), while casein degradation followed an nth-order model ($n=0.65$, $R^2=0.971$). Microbial growth was best described by the modified Gompertz model ($R^2=0.981$), and Arrhenius analysis yielded an activation energy of 42.6 kJ/mol. Sensor frequency decreased consistently with spoilage, with 5.0 cm plate spacing providing optimum sensitivity. Frequency shift showed strong relationships with log CFU, free fatty acids and casein ($R^2=0.960$ at 70 kHz; 0.948 at 50 kHz). Blind validation achieved 93.3% classification accuracy and a mean shelf-life prediction error of 1.2 days, with sensitivity and specificity above 90%.

A 756-entry spoilage library integrating physicochemical, microbiological and sensor parameters was developed. Overall, the study establishes an integrated, low-cost and non-destructive framework for rapid paneer spoilage detection and shelf-life prediction.

Keywords: Wireless sensing; FREQUENCY-Based gas sensor; Paneer spoilage; UHT paneer Secondary shelf life; Conducting polymer; Food safety