ABSTRACT

This study developed a passive high-frequency RFID gas sensor for real-time and non-destructive monitoring of milk spoilage. The sensor was evaluated using pasteurized and ultra-high-temperature (UHT) milk to assess its suitability for freshness detection and cold-chain monitoring. Pasteurized double-toned milk (DTM), toned milk (TM), and full-cream milk (FCM) were stored at 4, 10, 20, 37, and 45 °C, while UHT milk was studied at 10–45 °C. Shelf life decreased sharply with increasing storage temperature. For TM, it reduced from 350 h at 4 °C to 2.56 h at 45 °C, while the secondary shelf life of UHT milk decreased from 136.66 h at 10°C to 3.46 h at 45°C. Microbial growth was described using monophasic and biphasic Baranyi and Roberts models. Biphasic growth was observed at 4 °C, whereas monophasic growth occurred at 10–45 °C, with R^2 values of 0.97–0.99. Headspace SPME-GC-MS analysis identified acetone as the most consistent spoilage marker in both pasteurized toned and UHT milk. Based on this marker, a PEDOT:PSS/GO-NS/ZnO-NPs sensing layer was fabricated and deposited on a passive RFID tag. The resonance shifted from 13.70 to 13.75 MHz after sensor fabrication. A double-turn loop antenna with an inductance of 897 nH was used for wireless interrogation, and the loaded system showed a resonance at 13.70 MHz with S11 of -29.08 dB. Under controlled acetone exposure from 0–10 ppm, the sensor showed a linear inverse response with a sensitivity of -14.92 kHz/ppm and a detection limit of 1.71 ppm. It showed negligible response to acetic acid and remained stable up to 80–85% relative humidity. During milk spoilage, resonant frequency decreased with storage time and temperature and reached values associated with the end of shelf life. The sensor recovered close to its initial frequency within 1.3–1.5 min after flushing, confirming good reversibility. SEM, FTIR, and XRD supported the nanocomposite structure and VOC adsorption behaviour. Overall, the developed passive RFID sensor shows strong potential for wireless, non-destructive milk freshness monitoring and cold-chain quality assessment.

Keywords: Wireless sensing; RFID-Based gas sensor; Milk spoilage; UHT milk; Secondary shelf life; Conducting polymer; Food safety