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Non-Invasive Milk Quality Estimator Based on Capacitive Changes in Milk with Customized Electrode Receptacle †

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Abstract: An attempt is made to develop a system and an inexpensive device capable of estimating the quality of milk without opening the packaging. The experimental setup consists of a circuit and an electrode receptacle customized to the targeted milk packaging. A regression-based model is developed using the data capturing the change in capacitance and pH values over time to estimate the quality of milk. Using the setup, capacitance is measured which is then correlated to pH to obtain insights about quality. The results of the research and a prototype of the device are presented in the paper.

Keywords: non-invasive; capacitive changes; regression analysis

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1. Introduction

Milk is a complex media, comprising water, carbohydrates in the form of sugar lactose, fat, proteins (mainly casein, with smaller concentrations of other proteins), and mineral salts (Table 1). This makes milk a complete diet. Unfortunately, this also makes it an ideal breeding ground for microorganisms capable of spoiling the milk. Intake of spoiled milk can cause diseases and put a strain on the healthcare system. Monitoring the quality of milk is thus of paramount importance for ensuring food safety and human health. Currently, use-by date printed on packaged milk is used to get an estimate of the milk quality. These are based on an elementary estimate of the shelf-life and prove inadequate if the milk carton is exposed to extremes of temperature and humidity while in transit from manufactures to retailers [1]. In recent years researchers have begun exploring current technologies to monitor the quality of milk. Mahato et al., have developed a paper-based biosensor for the detection of alkaline phosphatase, ALP in milk [2]. ALP is a metalloprotein found in raw milk, which denatures after pasteurization. Ideally, pasteurized milk should be devoid of ALP. It is considered an important biomarker in quality control of milk. The limit of detection of the biosensor is 0.870 (±0.07) U/mL and the detection time is 13 min. Weston et al., have come up with an Anthocyanin-based sensor as an active use-by date indicator for milk [3]. From their study they have determined that an anthocyanin-agarose film is the optimum material for the best colorimetric response. The sensor undergoes a visible blue to purple to pink color change in response to varying lactic acid levels which varies with the degradation of milk quality and RGB analysis reveals a linearly increasing RCS between pH 6.8 and pH 4.0. Pisra et al., have fabricated starch-nano clay composite films loaded with methyl orange and bromocresol green for determination of milk spoilage [4]. During spoilage the pH of milk decreases from 6.7 to about 4 which is indicated by a change in color of the indicator. In this range of pH, the color of the Methyl orange-based film changes from yellow at pH 7 to pink at a pH of around 4. Similarly, the Bromocresol green changes from blue-green at pH 7 to yellow at pH of about 4. Luther et al., have assembled a Paper test card for the detection of adulteration in milk [5]. The test card can calorimetrically detect a variety of starches, urea, and the sugars glucose and sucrose with a sensitivity of over 90% at concentrations of the additives that are typically found in adulterated milk. To perform the detection milk needs to be pipetted onto the card. The detection time is 40 min. Lakade et al., have developed a nano sensor utilizing cysteine modified Ag nanoparticles for gradation of milk quality [6]. Cysteine helps in the binding of Ag nanoparticles and the lactic acid molecules. The composite exhibits a specific color depending on the concentration of the lactic acid. The authors have shown that the composite changes color from yellow to red-orange to violet with increasing concentration of Lactic Acid. Bhadra et al., have fabricated a wireless, passive pH sensor with an iridium/iridium oxide electrode and Ag/AgCl reference electrode, the resonance frequency of which is monitored at a distance of 5 cm from it using an interrogator coil and an impedance analyzer [7]. This setup was able to monitor in rea-time he quality of milk contained within a container. Potyrailo et al., have demonstrated the use of commercially available RFID tags to monitor milk freshness [8]. The sensor, which is attached to the side walls of the milk carton, detects the changes in the dielectric properties of the milk occurring due to the spoilage of milk. The sensor response is read by a pickup coil. The disadvantage of this is that the presence of any metal layer in the packaging interferes with the measurement. Wu et al., have developed a 3D printed 'smart cap' with embedded circuitry to detect changes in the dielectric constant of milk happening due to spoilage [9]. When the carton is flipped a small volume of milk is trapped within the capacitor plates. As the dielectric constant varies with quality, the resonance frequency of the LC tank also varies which is detected by means of an inductively coupled reader. Quirky, a crowd-sourced product design foundry, and GE have together developed Milkmaid, a new smart jug that automatically detects when milk has gone bad or run out and alerts the user via iPhone app [10]. Temperature, pressure and pH sensors are built into the base which are able to detect when too much acid has accumulated, indicating spoilage. However, no further information is available regarding its commercialization. All of the techniques however suffer from certain disadvantages which limits its practical use. The smart jug requires milk to be poured into it to function. A lot of the other methods as well require this, for e.g., the ALP detection paper sensor, the anthocyanin-based sensor of Weston et al., the starch films loaded with indicators (Pisra et al.), etc. RFID an NFC suffer from signal interference in case any metal layer is present in the packaging. Implementation of the smart cap requires modification of existing packaging. Some of the techniques require elaborate laboratory setup, sample preparation steps, need for trained professional to interpret the test results, time consuming procedures, need to maintain stringent environmental conditions like temperature, etc. There are certain techniques which are destructive in nature. Keeping in mind all these things we have tried to come up with a way to assess the quality of milk externally.

Table 1. Constituents of milk [11].

Water	87.2%
Lactose	4.9%
Total protein	3.5%
Casein	2.8%
Fat	3.7%
Mineral Salts	0.72%

2. Materials and Methods

We have attempted to develop a system that can monitor the pH and capacitance of a sample of milk contained within a PET bottle. The measurement of capacitance is performed non-invasively and non-intrusively through the use of an Electrode receptacle in which the bottle is placed. The time variation of capacitance and pH is used to build a regression model the results of which are presented in the Results section.

2.1. Measuring Capacitance

To measure the capacitance a capacitive voltage divider circuit is built using an Arduino Uno. The circuit comprises a reference capacitor C_1 and the capacitor under test C_T. The voltage at one end of C_T, A2 is pulled up to 5V and the voltage at the other end, A0 is measured, as illustrated in Figure 1a,b. The following formulae is used to calculate the C_T

$$C_T = V_{A0}C_1/(V_{A2} - V_{A0}), \quad (1)$$

This circuit is capable of measuring capacitances in the range pF–μF.

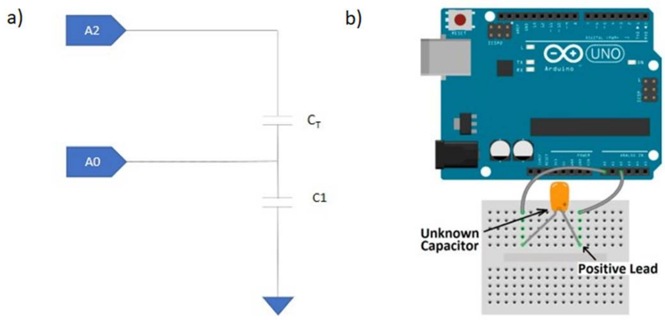

Figure 1: (a) Principle of operation of capacitance measurement and (b) Arduino circuit to measure capacitance

Figure 1.

2.2. Electrode Receptacle

To capture the capacitance a custom designed electrode receptacle is used which is illustrated in Figure 2. The electrode receptacle is assembled in a cardboard box using Al Heat sinks of dimension 4.5 cm × 6 cm. The dimensions of the cardboard box and the Al Heatsink electrodes may be customized according to the targeted packaging.

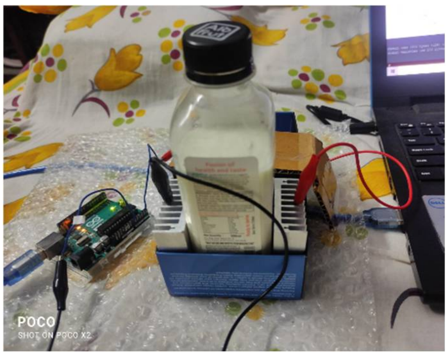

Figure 2. Electrode Receptacle.

2.3. Measuring pH

The pH of fresh milk is reported to be in the range 6.5–6.7 [1]. As the quality of milk degrades over time, the sugars present in milk are decomposed by bacteria and the milk becomes more and more acidic. As a result, a fall in pH is observed. To monitor the changes in pH a circuit is assembled using an Arduino Uno, an analog pH sensor with

BMC connector and a pH electrode. The probe is dipped into the milk to get an estimate of pH. The circuit is illustrated in Figure 3a,b.

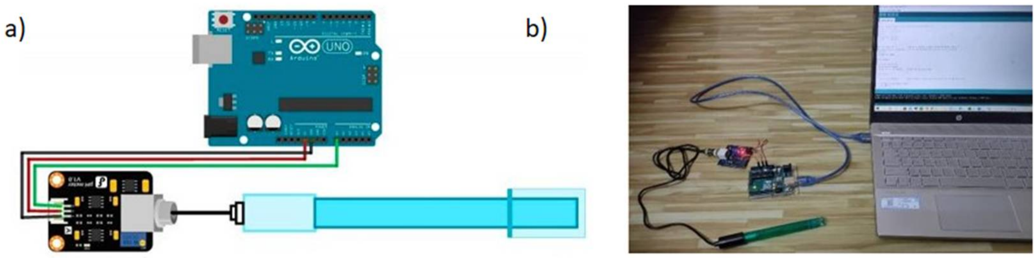

Figure 3: (a) Circuit to measure pH and (b) Arduino implementation

Figure 3.

2.4. Regression Analysis

A regression model is used to study the correlation between the pH and capacitance.

3. Results

When milk is kept at room temperature (around 30 °C), it takes around 8 to 10 h to be rendered unconsumable. With time, a rising trend in Capacitance is observed. From this it can be said that the dielectric constant, which is a physical parameter of the milk will also rise with time. The dielectric constant may be derived from the measured capacitance values by simple arithmetic, provided the plate dimensions, namely the plate area and the distance between the plates are known. Representative plots illustrating the trends in the change in capacitance and pH over time are illustrated in Figure 4a,b.

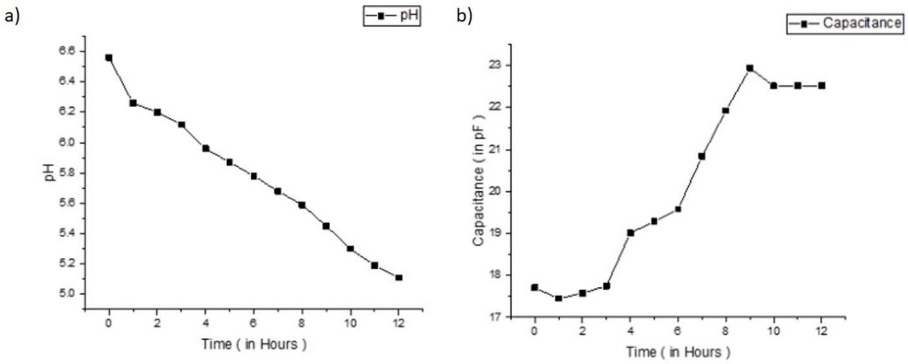

Figure 4: Time variation of a) pH and b) Capacitance

Figure 4.

Regression Analysis is used to study the relationship between the Capacitance and pH. For one of the representative plots, it is found that the two exhibit a correlation coefficient of 0.9414. This value is very near to 1 which indicates a strong positive relationship. A significance-F value of 1.59×10^{-6} indicates that the relationship is statistically significant. The R-square value for this fit is 0.8862. A plot illustrating the overlap of the Measured and Predicted values of Capacitance vs. pH is given in Figure 5.

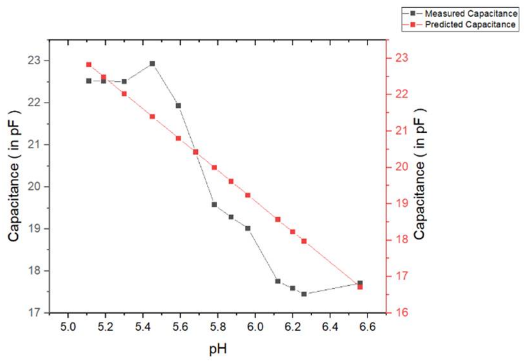

Figure 5. Capacitance (predicted and actual) vs. pH.

4. Discussion

The pH is a widely accepted indicator of milk quality, with the pH of perfectly good milk being in the range of 6.5–6.7 [1]. This relationship is illustrated in Figure 6. Most pH sensors are invasive and obtrusive in nature; hence it is not suitable for use in practice. Here we have shown there is a strong correlation between the pH and the measured Capacitance. Hence, we propose the use of Capacitance as a parameter to semi-quantitively estimate milk quality in practice.

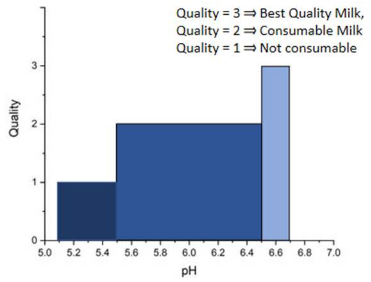

Figure 6. Estimate of quality from pH.

5. Conclusions

An attempt is made to develop a method to capable of estimating the quality of milk without opening the packaging. A circuit in conjugation with a customized electrode receptacle is used to monitor capacitive changes is milk which is correlated to pH. The developed regression model is used to get a representative pH for the sample from which an estimate of quality is ascertained. This was tried and tested to PET bottles. Customizing the method for other milk packaging is currently underway. This data driven approach coupled with external circuitry is of commercial significance and has the potential to be developed into an appropriate service in the market. To develop this into a full-fledged product rigorous data collection to train the model and electrode receptacles specific to targeted packaging will be needed.

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