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Original Article

Determination of the concentration of alum additive in deep-fried dough sticks using dielectric spectroscopy

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ABSTRACT

The concentration of alum additive in deep-fried dough sticks (DFDSs) was investigated using a coaxial probe method based on dielectric properties in the 0.3–10-GHz frequency range. The dielectric spectra of aqueous solutions with different concentrations of alum, sodium bicarbonate, and mixtures thereof were used. The correspondence between dielectric loss and alum concentration was thereby revealed. A steady, uniform correspondence was successfully established by introducing $\omega \cdot \varepsilon''(\omega)$, the sum of dielectric loss and conductor loss (i.e., total loss), according to the electrical conductivity of the alum-containing aqueous solutions. Specific, resonant-type dielectric dispersion arising from alum due to atomic polarization was identified around 1 GHz. This was used to discriminate the alum additive in the DFDS from other ingredients. A quantitative relationship between alum and sodium bicarbonate concentrations in the aqueous solutions and the differential dielectric loss $\Delta\varepsilon''(\omega)$ at 0.425 GHz was also established with a regression coefficient over 0.99. With the intention of eliminating the effects of the chemical reactions with sodium bicarbonate and the physical processes involved in leavening and frying during preparation, the developed technique was successfully applied to detect the alum dosage in a commercial DFDS (0.9942 g/L). The detected value agreed well with that determined using graphite furnace atomic absorption spectrometry (0.9722 g/L). The relative error was 2.2%. The results show that the proposed dielectric differential dispersion and loss technique is a suitable and effective method for determining the alum content in DFDSs.

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1. Introduction

The deep-fried dough stick (DFDS), or *Youtiao*, is a traditional and inexpensive Chinese breakfast food, which is popular in China. The major ingredients of DFDSs are dough, baking soda (sodium bicarbonate), and alum (hydrated potassium aluminum sulfate). The preparation process of DFDSs involves fermentation and frying at high temperature. When alum is not used, the DFDS is small and hard. However, when using alum the DFDS is big, golden in color, crispy outside, and has better sensory characteristics. During the cooking process, alum and sodium bicarbonate undergo the following chemical reaction:

$$2KAl(SO_4)_2 \cdot 12H_2O + 6NaHCO_3 = K_2SO_4 + 3Na_2SO_4 + 2Al(OH)_3\downarrow + 6CO_2\uparrow + 24H_2O \quad (1)$$

In this reaction, carbon dioxide gas is produced, while the $Al(OH)_3$ is formed as a floc. The aluminum hydroxide floc mixes with the flour to form a membranoid substance, which wraps around the CO_2. During the frying process, the carbon dioxide expands, making the DFDS swell. It is clear that there are chemical reactions involved. However, DFDS production also involves the following physical processes: floc aluminum hydroxide + flour → membrane covering carbon dioxide gas → expansion of the CO_2 when fried → DFDS swelling.

Alum is approved as a food additive by the U.S. Food and Drug Administration. However, it is toxic to humans in large quantities. Aluminum overload (alum, of course, includes aluminum in its chemical composition) in humans can cause diseases such as kidney dysfunction, softening of the bones, neurological disorders [1–4]. The commonly used methods for detecting aluminum in samples are atomic absorption spectrophotometry [5,6] and inductively coupled plasma-related detection technologies [7–9]. Although these technologies have high sensitivity and good accuracy, the equipment required is expensive and complicated to operate. Therefore, a fast, simple, and sensitive method for the detection and quantification of aluminum was needed. Some technologies have been developed based on the physical properties of foodstuff, including acoustic, optical, magnetic, mechanical, thermal, and fluid properties. These techniques have been explored to detect food quality, but each technique has its application field [10]. The dielectric properties of food materials describe how these materials interact with the electromagnetic field [11]. The interest in the dielectric properties of agricultural materials and food products has primarily centered on predicting heating rates that describe the behavior of the food when subjected to the high-frequency fields used in dielectric heating applications (so-called *novel thermal treatments*) [12]. This technology is not limited by the food variety. It is also simple, rapid, nondestructive, and sensitive [10]. Based on dielectric difference spectroscopy, dielectric properties have been used to control and evaluate food quality [13–20] and to detect food adulterated with other compounds [10,21,22].

The physical property to explain the effect of the electric field through a dielectric material is given by the Maxwell relations (Gauss law). Electric field is indicated as an epsilon (according to the notation suggested by the International Union of Pure and Applied Chemistry) and is defined as *permittivity*. Permittivity describes the displacement of the electric field, and therefore it is vectorially decomposed using a complex expression, where the real part describes the electric storage and is called *dielectric constant* (ε') and the imaginary part describes the *transformations* in other energies and is called *loss factor* (ε'') [23,24]. A relaxation spectrum, based on $\varepsilon'(\omega)$, usually occurs at frequencies smaller than 10 GHz (the angular frequency is given by $\omega = 2\pi f$, where f is the frequency) in which the absorption $\varepsilon''(\omega)$ is very small. The behavior here is that the spectrum increases with increasing ω. The behavior is mainly caused by the orientation and spatial polarization of the dielectric material. As frequency increases, a resonance spectrum is observed [$\varepsilon'(\omega)$ increases, then decreases, and then increases again as ω increases]. This is accompanied by the appearance of an absorption peak in $\varepsilon''(\omega)$ [at the same frequency as the *drop zone* in the $\varepsilon'(\omega)$ spectrum] [24]. To investigate the dielectric properties of alum, and to develop a new detection method for alum additives in DFDS, both the dielectric dispersion spectrum $\varepsilon'(\omega)$ and the absorption spectrum $\varepsilon''(\omega)$ of alum were studied in this work.

Even with a constant amount of alum and sodium bicarbonate, the DFDSs produced are different if different proofing and frying methods were applied in the production process. If these DFDSs were subjected to dielectric spectroscopy directly, the results would be different and would mainly reflect the different production processes used. Therefore, to avoid such influences on the dielectric spectrum, it is necessary to first extract the alum and sodium bicarbonate from the DFDS. It is well-known that alum and sodium bicarbonate are readily soluble in water. However, they are difficult to dissolve after the frying process. In turn, extraction and preparation of an aqueous solution of alum and sodium bicarbonate from DFDSs is an effective method for determining the dielectric spectrum of alum and sodium bicarbonate additives. However, Ryynänen [25] stated that the most important factor in determining the dielectric property is still water. Thus, it is difficult to observe the essential characteristics of food using the dielectric properties of electrolytic solutions. Therefore, to obtain the characteristics of the dielectric spectra of alum and sodium bicarbonate and to develop methods for detecting the nonaqueous food characteristics of components using dielectric spectroscopy, this study made use of standard samples of alum and sodium bicarbonate in addition to the DFDS solutions.