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A new approach to microwave food research: Analyzing the electromagnetic response of basic amino acids

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ABSTRACT

Measurement of the electromagnetic properties of food is important for its electromagnetic protection, microwave heating and sterilization. Much research had focused on describing the non-thermal mechanism of electromagnetism and locating its site of action. Amino acids are the basic units of proteins, and therefore their electromagnetic characteristics are central to understanding the transmission and loss of microwave energy in food and the non-thermal mechanism of electromagnetic effects. Herein, the dielectric properties and conductivity characteristics of solutions of basic amino acids, at an electromagnetic frequency of 2.45 GHz and at temperatures between 10 °C and 70 °C, have been measured. The results show that the dielectric constant and dielectric loss decrease with increasing temperature, for example, increase the temperature form 10 °C to 70 °C, the dielectric constant of lysine at 2% decreased from 77.259 to 68.601, and the dielectric loss decreased from 13.412 to 10.302, due to the decrease of the solution viscosity and the relaxation time, causing an increase of the dipole moment. Increasing the concentration of the basic amino acids leads to an increase of the dielectric loss, fix the temperature at 20 °C, the concentration of lysine increased from 0.5% to 10%, the dielectric loss increased from 10.191 to 23.232, which is related to the change of the conductivity. The conductivity has positive correlation with the concentration and temperature of the amino acid solution, fix the temperature at 20 °C, the concentration of lysine increased from 0.5% to 10%, the conductivity increased from 234 to 2840 μS/cm, and when the temperature was increased form 10 °C to 70 °C, the conductivity of lysine at 2% increased from 694 to 1347 μS/cm. The absorption properties of the solutions are characterized by the loss of reflection, and the absorption characteristics of the basic amino acids are related to the electromagnetic frequency, the concentration and the thickness of the absorbing layer, the variation of which affects the impedance matching. In this paper, through the study of the electromagnetic characteristics of basic amino acids in solution, a theoretical basis for the application of basic amino acids in microwave sterilization, as well as a mechanism for the microwave effect, are proposed.

1. Introduction

Among the 20 amino acids, the basic amino acids, including lysine, arginine and histidine, are highly polar compounds with a positive net charge at pH 7. Lysine is used in the Maillard reaction in the food industry, its side chain containing an ε-NH_3^+ (Kwak & Lim, 2004). Arginine is the most basic amino acid due to its extremely basic guanidine side chain. Due to the guanidine side chain, it is easy to react with other acids as well as form hydrogen bonds. The dissociation constant of the side chain of histidine, imidazolium, is 6.04, making its proton dissociation constant close to that of water. Therefore, histidine can act as both a proton donor and a proton acceptor. The alkaline amino acids are composed of amino and carboxyl termini together with different side groups, and their charge and mass have a spherical symmetric distribution with a certain dipole moment. They are responsive to the application of an electromagnetic field, giving them characteristic electrical or electrical polarization properties.

In recent years, a series of studies on dielectric properties, conductivity and microwave absorption have been performed in the context of environmental protection and military security, but this kind of research has been limited to areas of materials science such as carbon-based and metallic materials (Hou, Li, Zhao, Zhang, & Cheng, 2012; Idir, Weens, & Franchaud, 2009; Liang et al., 2009; Liu et al., 2013; Song et al., 2013; Song et al., 2012; Zhang, Liu, Liang, Zhang, & Che, 2013). These studies have provided reference data on the electromagnetic characteristics of the basic amino acids in aqueous solution,

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especially microwave absorption properties, barely reported in the field of food, which can measure the absorption of electromagnetic wave energy. Absorbing materials can be divided into two classes—dielectric loss and magnetic loss—according to their energy-loss mechanism (Yang, Ye, Lin, & Liu, 2015b). In the present study, the main component of the aqueous solutions of basic amino acids is water, a non-magnetic material with relative permeability 1, so the aqueous amino acid solutions are classed as dielectric-loss type, which could produce polarization relaxation under the action of electromagnetic wave, so that so as to convert electromagnetic energy into heat energy (Zhou, Chu, & Hu, 2006) . In general, the dielectric constant of a material indicates its ability to store electromagnetic energy, and the dielectric loss indicates the ability to consume electromagnetic energy (Tyagi, Baskey, Agarwala, Agarwala, & Shami, 2011). Dielectric relaxation is central to understanding the nature and origin of dielectric loss: relaxation time is a measure of the mobility of the molecules (dipoles) that exist in a material, when an electric field is applied to any material, the latter will consume a certain amount of energy and transform it into heat energy (Yakuphanoglu, Yahia, Senkal, Sakr, & Farooq, 2011). Constant collisions cause internal friction so that the molecules turn slowly and exponentially approach the final state of orientation polarization with relaxation time (El-Ghamaz et al., 2014). According to Debye theory, dielectric properties are connected with conductivity, and are important indices to evaluate the ability to absorb electromagnetic waves (Bollen et al., 2013; Huynen et al., 2011). Reflection loss (RL) is used to characterize the wave-absorbing properties. In the process of absorption, the conductivity of the electric dipole is very important (Chung, 2001); the reflection has a functional dependency on σ/μ and $1/f$ (σ: Conductivity; μ: Magnetic permeability; f: Frequency), and therefore, both an increase in the conductivity and a decrease in the permeability have the effect of increasing the amount of reflection (Ye et al., 2014).

These electromagnetic parameters are interrelated. The dielectric properties can be expressed as

$\varepsilon^* = \varepsilon' - j\varepsilon''$ where ε' is the dielectric constant, ε'' represents dielectric loss, $j = \sqrt{-1}$, and ε^* is the dielectric constant relative to free space. The two sources of the dielectric loss are conductive loss and dipole loss (Ali, Soliman, Saadeldin, & Sawaby, 2014). The dielectric loss mechanism of microwaves of a given frequency can be expressed as:

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma = \varepsilon''_d + \frac{\sigma}{\varepsilon_0 \omega}$$

where ε''_d is the loss caused by rotation of the dipole, ε''_σ represents the loss caused by ionic conductivity, σ is the conductivity, ω is the angular frequency, and ε_0 refers to the dielectric constant in free space. The electrical conductivity is related to the dielectric loss. Based on the free-electron theory, in the basic amino acid solution, the positive ion can form a uniform electric field, and the free electrons move forward along the direction of the electric field, the electrical conductivity can be estimated from the dielectric loss in an alternating electric field (Shi et al., 2008):

$$\sigma \approx 2\pi f \varepsilon_0 \varepsilon''$$

The permittivity and permeability are important for RL, as expressed by (Zhu et al., 2010)

$$\mathrm{RL(dB)} = 20\ \lg\left|\frac{Z_{in}-1}{Z_{in}+1}\right|$$

$$z_{in} = \sqrt{\frac{\mu_r}{\varepsilon_r}} \tanh\left(j\frac{2\pi f d}{c}\sqrt{\mu_r \varepsilon_r}\right)$$

where d is the thickness of the absorbing layer, c is the speed of electromagnetic wave propagation in a vacuum, and ε_r and μ_r are the relative complex permittivity and permeability.

In this paper, the dielectric properties and conductivity of the three basic amino acids were measured at a microwave frequency of 2450 MHz and a temperature range of 10 °C to 70 °C. It was observed that the dielectric properties and conductivity of the three basic amino acids were related to the concentration and temperature of the solutions. The wave-absorbing properties showed that although the basic amino acids in aqueous solution had good microwave-absorbing abilities at this microwave frequency, the absorption effect was associated largely with the polarity of the water molecules and the charge of the amino acids. The effect of the electromagnetic field on the side chains of the basic amino acids was to induce their molecular polarization. This provides a theoretical basis for the application of microwaves to basic amino acids (e.g., for sterilization, re-heating, thawing and other food processing), and insights into the mechanism of the effect of microwaves on biological materials. This allows various biological issues to be addressed from the point of view of physics, and may also stimulate the development of cross-disciplinary research in bio-electromagnetics, materials science, food science, physics and engineering. The electromagnetic properties of amino acids are of great significance to the study of their response to electromagnetic field stimulation, the spatial distribution in the field, as well as energy absorption and conduction.

Parameters and definitions:
RL: Reflection loss (dB)
σ: Conductivity (S/m)
μ: Magnetic permeability (H/m)
f: Frequency (Hz)
ε': Dielectric constant
ε'': Dielectric loss
ε''_d: The loss caused by rotation of the dipole
ε''_σ: The loss caused by ionic conductivity
ω: Angular frequency
ε_0: Dielectric constant in free space
d: Thickness of the absorbing layer (m)
c: The speed of electromagnetic wave propagation in a vacuum (m/s)
ε_r: The relative complex permittivity
μ_r: The relative permeability.

2. Materials and experimental

2.1. Materials

L-Lysine, L-arginine and L-histidine, BR-level, were purchased from Sinopharm Chemical Reagent Co., Ltd. Their dielectric properties were measured using a vector-network analyzer (E5071C, Agilent, Santa Clara, CA, USA) with an open-ended coaxial line connected to a dielectric probe (85070E, Agilent, Santa Clara, CA, USA). The measurement of conductivity was performed using an LA-EC20 laboratory conductivity meter (HACH, USA).

2.2. Dielectric measurement

The dielectric constant and dielectric loss were determined using the coaxial probe method (Hoshina, Kanai, & Miyakawa, 2001), in which the system consisted of a network analyzer, 85070E dielectric probe, probe cable, computer and test software. The measured frequency was 2450 MHz (Microwave oven heating frequency). For calibration of the instrument, the network analyzer needed 30 min per heating after opening, the measuring frequency was set between 2.4 and 2.5 GHz, so that the midpoint frequency was 2.45 GHz, and the temperature was set to the ambient temperature measured by the thermocouple. The probe was calibrated for air, the resistor, and de-ionized water, in turn. For sample measurement, solutions were prepared with concentrations of 0.5%, 1%, 1.5%, 2%, 2.5%, 4%, 6%, 8%, and 10% (for lysine and arginine) and 0.5%, 1%, 1.5%, 2%, and 2.5% (for histidine, limited by solubility). The solvent involved in this paper is deionized water. The concentrations of each amino acid mentioned in the form of % mean