

# Dielectric properties investigation of commercial dairy whitener at 2.45 GHz

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Received: 10 August 2025 / Accepted: 05 October 2025 / Published online: 23 April 2026

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**Abstract:** Dairy whitener can be contaminated by pathogens, leading to major health concerns. Dielectric properties can detect and help in treatment of such contaminations. Hence, dielectric properties relevant to dielectric heating were investigated at 2.45 GHz which is a common ISM frequency. These properties (Dielectric constant and dielectric loss factor) were determined using cavity perturbation method with the help of a vector network analyzer (VNA) in moisture and temperature range 3 – 17% (w.b) and 15-65 °C, respectively. Present studies showed that dielectric constant and loss factor increased with temperature and moisture content. Calculated penetration depth based on these properties decreased with moisture and temperature. A 2nd order regression equation was generated to know dielectric properties values at 2.45 GHz at desired moisture content and temperature, for which  $R^2$  is 0.9947.

**Keywords:** Dairy whitener; Dielectric properties; Microwave heating; Penetration depth.

## Introduction

Dairy whitener is a fine powder made by dehydrating liquid milk through several drying processes. It is a formulated product used as a substitute to fresh milk, cream or evaporated milk especially in tea, coffee and drinking chocolates. Its usage in food industry is majorly due to its long shelf life and convenience being a ready-made product. Like all other food powders, dairy whitener is prone to pathogenic/bacterial contamination. It can happen if

the manufacturing environment or the milk fed to spray dryer is contaminated (Rotronic, 2024). Bacteria like *Cronobacter sakazakii* and *Salmonella* spp. can even survive the spray-drying conditions before packaging of dairy whitener. Recently, infant powder formula was recalled in February, 2022 related to contamination concerns (CDC, 2022). Earlier in 2006, milk related outbreak was reported by Centers for Disease Control and Prevention (CDC) in USA resulting 36 infections. This highlights the importance of processing dairy whitener to ensure safety, in line with established industry practices.

Conventional methods including thermal treatments of powders are ineffective due to low thermal conductivity of powders. It also requires longer heating time (Li et al. 2017; Pankaj et al. 2022). Protein denaturation and poor final quality are some of the disadvantages of high temperature treatments (Karagül-Yüceer et al. 2001). Chemical treatment of food powders is not considered safe and are not effective for pathogens like salmonella (Cox et al. 2000). One of the effective alternatives in food industry is microwave heating/ pasteurization which is relatively new and rapid technology. In microwave heating, heat is generated from within the material as compared to conventional methods where heat is transferred from source to material having temperature difference. Hence, microwave heating is localized heating. Other advantages include process automation, reduced thermal gradients, heating uniformity, better final product quality and high energy density (Rynnänen, 1995; Trabelsi et al. 2009; Guo et al. 2010; Pankaj et al. 2020).

To develop microwave heating/pasteurization protocol, knowledge of dielectric properties of the material is important. Dielectric properties which include dielectric constant and dielectric loss control how material under test is going to behave in applied electric field. Dielectric constant explains the storage of electromagnetic (EM) energy within the material. Dielectric loss gives the energy dissipation from the material. These parameters are commonly called complex permittivity ( $\hat{\epsilon}$ ) which describe dielectric properties and control the heating protocol (Nelson and Trabelsi, 2006; Trabelsi, 2015). Such heating is also called dielectric heating. Complex permittivity is mathematically given by following relation:

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$$\epsilon^* = \epsilon' - j\epsilon''$$

here,  $\epsilon'$  = dielectric constant and  $\epsilon''$  = dielectric loss factor. Factors which affect dielectric properties include moisture content, frequency temperature and material's chemical composition. There are specific frequencies including 13 MHz, 27 MHz, 40 MHz, 915 MHz, 2.45 GHz and 5.8 GHz which are worldwide used for industrial, scientific and medical applications and are called industrial, scientific and medical (ISM) frequencies. 2.45 GHz is the most popular heating/ pasteurization frequency which falls in microwave range. Microwave ovens used in households also work at 2.45 GHz.

In literature, Liu et al. (2018) and Zhu et al. (2015) investigated the frequency and temperature dependent of dielectric properties of raw, whole and skim milk. Zhong et al. (2017) and Dag et al. (2019) studied dielectric properties of infant milk powder and no-fat milk powder, respectively. Pankaj et al. (2022) have investigated broadband dielectric properties of some low moisture powders including chicken eggshell using cavity perturbation method. Present studies aim to measure moisture and temperature dependent dielectric properties (dielectric constant and loss factor) of dairy whitener at 2.45 GHz which may be useful for dairy whitener heating/disinfections.

## Materials and Methods

### Material

Nestle Everyday dairy whitener (400 g) was used in present studied and was purchased from a local store in Sangrur, Punjab. It contained 20 g protein, 57.8 g carbohydrate, 46 g total sugar, 18 g sucrose, 15 g total fat, 9.2 g saturated fat and 569 mg sodium, per 100 g. It was taken out of the packet and stored in the small airtight polybags at room temperature.

### Moisture content, density determination and sample preparation

Moisture content of dairy whitener was determined by AOAC (1998). For this, 2 g dairy whitener sample was taken in forced-air oven for 1 hour at a temperature of 130 °C. The original moisture content was found to be 3% (w. b) by repeating the procedure three times. A cylindrical container was used to find the bulk density of dairy whitener. It has 1 cm radius and 3.225 cm height. Bulk density of dairy whitener was found to be 0.551 g/cm<sup>3</sup>. Tapped density was determined by tapping the cylinder 15 times from a height of 2 cm (Bansal et al. 2015). Tapped density of original milk sample was 0.557 g/cm<sup>3</sup>.

Dairy whitener samples of ~7%, 11%, 14%, 17% were prepared by adding desired deionized water in 3% original sample. Desired water was introduced gradually as fine droplets while continuously mixing the sample in plastic bag. Airtight zip lock

bags were used to seal these sample and then were put in refrigerator at 10 °C for 24 hours. Samples were shaken thrice a day. Before taking measurements, samples were kept at room temperature for 6 hours to attain equilibrium. Tapped densities of all these samples were calculated and were 0.497 g/cm<sup>3</sup>, 0.583 g/cm<sup>3</sup>, 0.610 g/cm<sup>3</sup>, 0.542 g/cm<sup>3</sup>. Sample photographs at various final moisture contents are given in fig 1.

### Dielectric Properties Measurement

The measurement system used in present studies consists of a two port VNA (Agilent ENA series E5071C), a rectangular resonant cavity of 2.45 GHz, a thermocouple and heating element. Resonant cavity works in TE<sub>10</sub> mode which represents that electric field only exist traverse to cavity axis. This mode is used as the electric field is maximum at cavity centre where sample has to be inserted. This mode was used as fundamental transverse electric mode to maximize measurement sensitivity. Dimensions of the resonant rectangular cavity are 220.6 mm x 109.2 mm x 54.6 mm. VNA is itself the source of microwave and also analyse the transmitted field with the help of an internal computer. Any external computer is not required.

Resonant cavity of 2.45 GHz is placed on two stands and was connected to VNA through N-type connectors. More details about the measurement set up are provided in Pankaj et al (2024). Dairy whitener sample was filled in a quartz tube (Sigma –Aldrich Z562262-1EA) having low loss. It's outer and internal diameters were 4.95 and 4.15 mm, respectively. The length of the tube was 177.8 mm. Heating element for raising the temperature of sample was cylindrical and can accommodate quartz tube. This whole set up was same as that of earlier used by Pankaj et al. (2024).

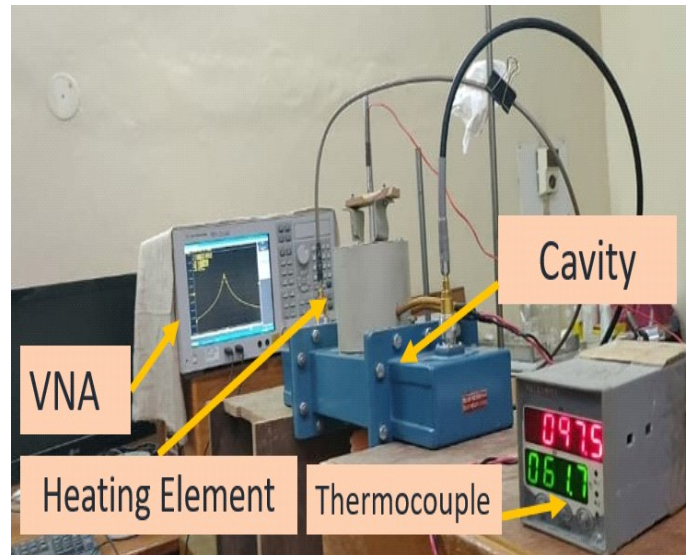
In general, changes in magnitude and phase of the incident and transmitted/reflected signal from the sample are studied to measure dielectric properties of the sample under test. VNA itself is a source and receiver of the transmitted or reflected signal. Laboratory temperature was maintained at 20 °C. The method used for present studies is cavity perturbation method. It is based upon the principle that resonant frequency of the cavity will shift when EM radiation passes through a little sample filled in the quartz tube which is placed at the centre of 2.45 GHz resonant cavity. This will cause a decrease in quality factor of the resonant cavity (Palta et al. 2020).

Dairy whitener samples with different moisture contents were filled in quartz tube at corresponding bulk density and shift in the resonant peak was noticed along with quality factor. Dielectric constant and loss factor ( $\hat{\epsilon}'$  and  $\hat{\epsilon}''$ ) can be calculated by using the following relation (Pankaj et al. 2020):

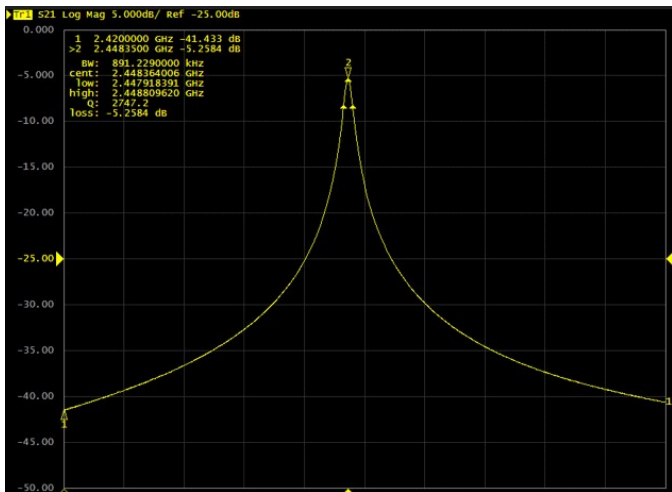
$$\epsilon' = 1 + \frac{V_c(f_c - f_s)}{2V_s f_s} \quad \text{and} \quad \epsilon'' = \frac{V_c}{4V_s} \left( \frac{1}{Q_s} - \frac{1}{Q_c} \right)$$



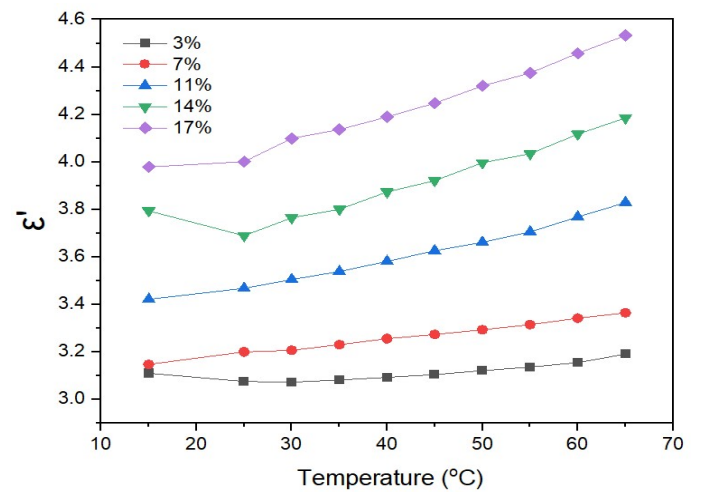
**Fig. 1** Sample photographs at various moisture contents (% w. b)



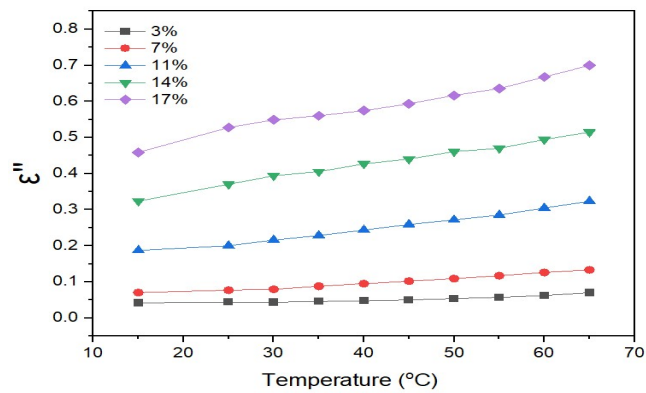
**Fig. 2** Real time photograph of dielectric properties' measurement setup



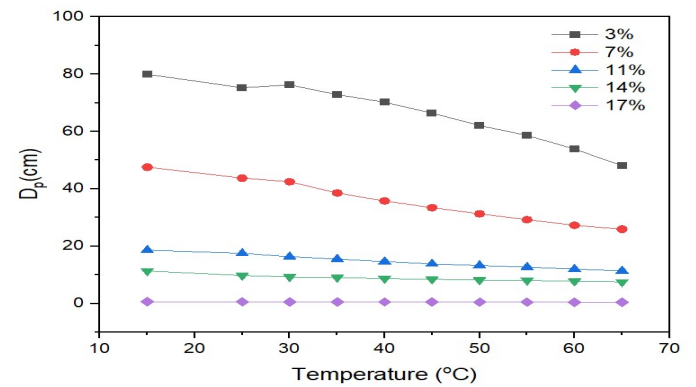
**Fig. 3** Resonant peak of empty cavity of 2.45 GHz



**Fig. 4** Variation of dielectric constant of dairy whitener with moisture and temperature at 2.45 GHz



**Fig. 5** Variation of dielectric loss factor of dairy whitener with moisture and temperature with moisture and temperature at



**Fig. 6** Penetration depth variation for dairy whitener with moisture and temperature at 2.45 GHz

where,  $V_c$  and  $V_s$  are the volume of the resonant cavity and the volume of sample in cavity, respectively.  $f_c$  and  $f_s$  are the resonant frequency of the resonant cavity and cavity having sample, respectively.  $Q_s$  is the quality factor of cavity having sample whereas  $Q_c$  is the quality factor of empty cavity.

**Results and Discussion**

**Dielectric properties**

The dielectric properties of dairy whitener were determined five moisture contents of ~3, 7, 11, 14 and 17% (w. b.) at 2.45 GHz at different temperatures ranging from 15 – 65 °C. Dielectric constant and loss factor both were plotted on linear scale with temperatures at all moisture levels. Fig 4 shows the variation of dielectric constant of dairy whitener at different temperatures from 15 – 65 °C. Dielectric constant shows variation from the value of ~3.1 at lower temperature for 3% (w. b.) to ~4.53 at higher temperature for 17% (w. b.) moisture. It is clear that dielectric constant increased with increase in moisture content from 3-17% (w. b.) as well as with temperature from 15-65°C. Increase with moisture content is based on the mechanism that how microwave energy interacts with bound and free water in dairy whitener sample (Tang, 2005). Free water is not available for lower moisture contents and hence, the increase in dielectric constant with moisture is small as compare to higher moisture contents where free molecule is available.

Fig 5 shows the variation of dielectric loss factor with that of moisture and temperature. It is evident that dielectric loss factor increased with increased of temperature for all moisture levels. It increased from ~0.04 -0.69 from 3 – 17% (w. b.). This increase is more pronounced for higher moisture level, especially at 17% (w. b.) as shown in fig 5. It is clear that moisture content and temperature both plays a significant role in dielectric properties variation. These properties arise from different kinds of polarization mechanism in which ionic and dipolar polarizations are dominant generally. Out of these, ionic is dominant below ~1 GHz and dipolar above ~1 GHz. As 2.45 GHz is a microwave ISM frequency, dipolar polarization is supposed to cause the major change in dielectric properties because above 1 GHz, ions are no longer able to follow the applied field. On the other hand, dipoles rotate faster to applied field with can give rise to friction and results in heat/energy loss. It may contribute to an increase in dielectric loss factor (Wang et al. 2011). Free water availability

increases as moisture content and temperature goes up which may cause an increase in dielectric properties as shown in figs 2 and 3.

**Modelling of dielectric properties**

A 2nd order predictive equation was generated using Wolfram Mathematica (14.2, Wolfram Research, Champaign, IL, USA), a computational software widely used for symbolic and numerical analysis (Bansal et al. 2016). This equation can be used to know the dielectric constant and dielectric loss factor values for desired moisture content in 3-17% (w. b.) range and temperature range 15-65 °C, and generalised for both  $\epsilon'$  and  $\epsilon''$ , as under:

$$y = a_0 + a_1M + a_2T + a_{11}M^2 + a_{12}MT + a_{22}T^2$$

Where, y is dielectric constant or dielectric loss factor. M and T are the values of moisture content and temperature  $\hat{a}'$  and  $\hat{a}''$  values have to be predicted. Table 1 summarize the values of coefficient of regression up to four decimal points are given as  $a_0, a_1, a_2$ , etc. as given in the equation with R2 >99%.

**Penetration depth**

Penetration depth (Dp) is the depth into sample where incident electromagnetic (EM) power decreases to 1/e (~37%) of its original value at surface if it falls normally to surface (Sosa-Morales et al. 2010). It is given by following formula:

$$D_p = \frac{c}{2\pi f \sqrt{2\epsilon' \left[ \left( \sqrt{1 + \left( \frac{\epsilon''}{\epsilon'} \right)^2} \right) - 1 \right]}}$$

here, Dp is Penetration depth, f is frequency used (Hz) and c = 3 x 10<sup>8</sup> m/s. DP is calculated at 2.45 for dairy whitener corresponding to all temperatures (15-65 °C) and moisture range (3 - 17% w. b.). DP decreased with increase in moisture content and temperature for dairy whitener. Fig 6 shows the penetration depth for present studies. Lower penetration depth means there will be more surface heating whereas higher penetration depth is related to better and uniform heating of the sample under test.

**Conclusion**

Dielectric properties (dielectric constant and dielectric loss) of commercial dairy whitener sample were determined at 2.45 GHz in moisture range 3 – 17% (w. b.) and temperature range 15-65 °C . Results showed that both dielectric constant and dielectric loss increased with moisture as well as temperature for entire range. Penetration depth for dairy whitener was found to be decreasing with respect to increase in moisture and temperature values. The

**Table 1:** Coefficients of 2<sup>nd</sup> order regression equation

Coefficients	$\epsilon'$	$\epsilon''$
$a_0$	3.1936	0.0674
$a_1$	-0.0152	-0.0167
$a_2$	-0.0088	-0.001
$a_{11}$	0.0033	0.0022
$a_{12}$	0.0007	0.0003
$a_{22}$	0.0001	0

2nd order regression equation is derived to know the values of dielectric properties at any desired moisture and temperature in the given range. This study may provide essential insights for dairy whitener' efficient use in microwave-based processing and quality evaluation.

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