








A Microwave Spectroscopy Study for Gluten-Free Bread Doughs

Luigi Di Michele , *Member, IEEE*, Matteo B. Lodi , *Member, IEEE*, Giacomo Muntoni , *Member, IEEE*,
Andrea Melis , Federica Di Prima, Ferdinando Nunziata , *Senior Member, IEEE*,
Giuseppe Mazzarella , *Life Member, IEEE*, and Alessandro Fanti , *Senior Member, IEEE*

I. INTRODUCTION

Abstract—Gluten-free products market is experiencing a noticeable growth, due to the worldwide increase of celiac disease and intolerances. Among gluten-free products, bread is the most challenging food to replace, since gluten-free flours have a complex microstructure and processing. Microwave (MW) dielectric spectroscopy can help to provide insights in food composition and structure. However, the dielectric spectra of gluten-free doughs have never been investigated. In this study, we systematically investigate the dielectric properties of gluten-free doughs. We analyzed the dielectric response of raw ingredients using an open-ended coaxial probe in the frequency range $f \in [0.2, 4]$ GHz and then evaluated the feasibility of using mixing formulas to predict the gluten-free dough spectra. Homogenization formulas are not able to predict the MW dielectric response of gluten-free doughs. Therefore, we tested the multipole Debye, Cole-Cole, and the Havriliak–Negami dielectric models. The three-pole Cole-Cole model is the best dielectric model, resulting in an average relative percentage error of 0.84% and 0.65% on the real and imaginary parts, respectively. After identifying the best dielectric model, we have used it to fit the spectra of 54 doughs with variable water, yeast, and salt content, thus providing, for the first time, an MW spectroscopy framework to define the dielectric properties of this food material. From our investigations, it turned out that salt increases the dielectric losses, yeast affects the energy storage, but water plays the main role in determining doughs properties. Comparing the dielectric spectra of gluten and gluten-free doughs, we observed relevant differences for dry, wet, yeast-free, and salt-free cases, but a similar dielectric spectrum was found for the reference dough composition.

Index Terms—Bread dough, dielectric materials, dielectric measurements, dielectric spectroscopy, food manufacturing, microwave (MW) measurements, open-ended coaxial probe (OCP).

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Luigi Di Michele, Matteo B. Lodi, Giacomo Muntoni, Andrea Melis, Federica Di Prima, Giuseppe Mazzarella, and Alessandro Fanti are with the Department of Electronic and Electrical Engineering, University of Cagliari, 09123 Cagliari, Italy (e-mail: alessandro.fanti@unica.it).

Ferdinando Nunziata is with the Department of Information Engineering, Electronics and Telecommunications, Sapienza University of Rome, 00184 Rome, Italy.

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THE increasing incidence of celiac disease and the growing adoption of gluten-free diets have highly increased the popularity of gluten-free products worldwide [1], [2], [3]. Gluten, a protein found in various cereals, plays a fundamental part in defining the structural attributes of dough [4], [5]. It is primarily responsible for its elasticity and cohesion, which are key aspects of baked product quality [5], [6]. The absence of gluten, however, introduces nontrivial complications in replicating these functional traits of gluten-free products [4], [5], [6].

To address these challenges, gluten-free doughs are typically formulated using a combination of alternative flours, starches, and hydrocolloids that aim to replicate the properties of gluten [5]. The success of these alternative compositions depends on the careful selection and precise dosage of ingredients. However, despite a significant progress in this area, gluten-free doughs often exhibit suboptimal rheological characteristics compared to their gluten-containing counterparts [6], highlighting the need for better formulations. Therefore, gluten-free doughs are more difficult to handle from an industrial point of view, and a thorough characterization and deep knowledge of their physical properties may foster the advancement of this innovative class of food products.

Dielectric characterization through the use of microwave (MW; $f \in [0.3, 300]$ GHz) sensors has emerged as a valuable analytical tool to study the characteristics of foods materials [12], [13], [14]. In particular, some previous studies have focused on understanding and predicting the dielectric response of bread samples using MW devices (see Table I) [7], [8], [9], [10]. Most of these studies used an open-ended coaxial probe in the frequency range from $f \in [0.1, 8.5]$ GHz, disregarding modeling and compositional analysis. Therefore, given the lack of literature on normal bread and doughs, it must be recognized that the knowledge gap is further evident and urgent for gluten-free doughs. Therefore, there is a need for dedicated MW spectroscopy studies applied to gluten-free doughs and breads.

MW spectroscopy, by modeling the frequency response of complex dielectric permittivity $\varepsilon(f) = \varepsilon' - j\varepsilon''$, allows one to provide essential information of a material sample. For food materials, MW spectroscopy can help in understanding water distribution and ingredient concentrations, while ensuring the tracking of the physiochemical changes occurring during their processing [15], [16], [17]. A proper modeling of the dielectric

TABLE I
STATE-OF-THE-ART ANALYSIS OF MICROWAVE DIELECTRIC SPECTROSCOPY OF BREAD AND DOUGH

| Frequency Range (GHz) | Measurement Method | Modeling (Yes/No) | Composition Effects (Yes/No) | Ref. |
|-----------------------|-------------------------|---|------------------------------|------|
| 0.6–2.45 | Open-ended coaxial line | No | No | [7] |
| 0.3–6 | Coaxial cell | No | Yes | [8] |
| 0.1–1.8 | OCP ¹ | Yes (Mixing eqs., Polynomial fitting) | No | [9] |
| 0.5–8.5 | OCP | Yes (Mixing eqs., Debye, Cole-Cole fitting) | No | [10] |
| 0.5–8.5 | OCP | Yes (Cole-Cole fitting) | Yes | [11] |

¹OCP = Open-ended coaxial probe.

properties of a target material is, hence, essential to understand the molecular interactions and dynamics within complex systems, such as bread doughs [10], [18]. In this framework, several MW dielectric models are available. The Debye model, derived from the linear response theory for describing the polarizability of a material, accounts for dielectric relaxation of uniformly dispersed molecules [19]. While effective for simpler systems, the Debye model can be limited when applied to more complex materials, such as doughs, that are heterogeneous, complex, and nonlinear materials, where multiple relaxation processes, attributable to several different molecules, often occur [20]. To overcome these limits, it is possible to use multipole Debye models or rely on the Cole-Cole model [21]. The Cole-Cole model is a generalized dielectric model that is able to describe a distribution of relaxation times and the broadening of the spectrum. The multipole Cole-Cole model has proved to be highly effective in reflecting the broadband response of heterogeneous materials [22]. Another model often employed is the Havriliak–Negami model, which has been designed to describe the dielectric behavior of materials with complex and heterogeneous molecular dynamics through additional broadening and symmetry parameters [23].

So far, the MW dielectric response of gluten-free dough has not been investigated, and therefore, the model to interpret it is unknown. We hypothesized that these more sophisticated MW spectroscopy models can be applied to understand the dielectric response of gluten-free doughs. Indeed, previous research on gluten-containing doughs, especially Carasau bread doughs [10], [11], [18], [24], [25], has identified the three-pole Cole-Cole model as the most accurate (average percentage relative error below 5%) for capturing their dielectric behavior under different compositions (i.e., varying water content, yeast concentration, and salt amount). However, the best model for the MW spectra of gluten-free bread dough has yet to be found.

In this study, we systematically investigate the dielectric properties of gluten-free doughs. To this aim, we analyzed the dielectric response of raw ingredients using an open-ended coaxial probe (OCP) and then evaluated the feasibility of using mixing formulas to predict the gluten-free dough spectra. To provide a first and in-depth understanding, we tested the multipole Debye, Cole-Cole, and the Havriliak–Negami dielectric

models to assess their applicability to gluten-free doughs. Once the best dielectric model is found, it is employed to fit the spectra of 54 doughs with variable water, yeast, and salt content, thus providing, for the first time, an MW spectroscopy framework to obtain the dielectric characterization of this food material.

The rest of this article is organized as follows. In Section II, the dielectric behavior of individual dough components is analyzed, and the measurement setup, implemented technique, and the analysis carried out on the data obtained from the measurement process are described in detail. In addition, this section discusses MW spectroscopy characterization, mixing formulas for MW property prediction, and dielectric spectroscopy models, providing the theoretical framework for the study. In Section III, the experimental results are presented, showcasing how the obtained data were used to extrapolate information on the dielectric properties of gluten-free doughs. The limitations of mixing formulas in predicting dielectric behavior are highlighted, and the need for more accurate models is emphasized. A comparison between the results obtained for gluten-free doughs and those for gluten-containing doughs (from previous studies that adopted the same procedure) is also provided. Finally, Section IV concludes this article, summarizing the findings and discussing their implications.

II. DIELECTRIC CHARACTERIZATION

A. Context

There is a large variability of gluten-free products, manufactured using native and modified starches blended with different hydrocolloids or other improvers [6]. Therefore, in this study, we analyze two sets of gluten-free doughs prepared using mixtures of two different commercially available gluten-free flours, distilled water, yeast (*Saccharomyces cerevisiae*), iodized salt, and vegetable extra-virgin olive oil. It should be stressed that previous research focused on gluten-containing doughs [10], [18], [24], [25], [26], [27] was limited to four ingredients, without taking into account the oil in the dielectric response of the dough. The addition of oil in this case aims to enhance the dough's malleability and achieve properties as close as possible to those of commonly used doughs. Therefore, this study investigates the MW dielectric properties of gluten-free doughs, incorporating

oil at a fixed concentration and evaluating its potential impact on the gluten-free dough microstructure and dielectric properties.

It is known that variations in water, salt, and yeast concentrations significantly affect the chemical and physical properties of doughs [5], [6], [28], [29]. Some general and a priori remarks about the effects of these ingredients on doughs and dielectric properties can be given as follows.

- 1) *Water*: Higher water content softens the dough [30], [31], [32], increasing its fluidity and modifying the balance between the continuous liquid phase and the dispersed solid particles. Excessive water, however, may weaken the dough structure, reducing its ability to retain gas [30], [31], [32]. From a dielectric point of view, water content may affect the free and bounded water relaxations and polarization, thus greatly impacting on the values of dielectric permittivity [18].
- 2) *Salt*: Salt acts as an osmotic regulator and influences yeast activity [30], [31], [32]. Higher salt concentrations can inhibit gas production, limiting dough expansion during leavening [10]. From the dielectric point of view, an increase in salt amount would determine the availability of free charges that would lead to an increase in losses [10], [11], [18].
- 3) *Yeast*: Yeast concentration determines the rate of carbon dioxide production [30], [31]. Yeast is a living material, and it concurs to the dynamic modifications of the dough, especially increasing the fraction of gases in the sample. Higher yeast levels accelerate leavening but may lead to less uniform bubble distribution [10]. Therefore, from a dielectric point of view, it can be expected that the yeast concentration would imply a lowering in the dielectric properties [10]. However, leavening is a complex and nonlinear process, which calls for thorough experimental and spectroscopic modeling.

Recent studies on semolina-based doughs have shown that dielectric properties are closely linked to their composition and microstructure [33]. In particular, interactions between water and carbohydrates, as well as the presence of salt, significantly influence dielectric permittivity and losses. The addition of salt increases dielectric losses due to the presence of free ions, which enhance conductivity effects. Furthermore, it has been observed that water contributes both as a dipolar component and as a plasticizer, modifying the balance between the gluten (or starch) network and the surrounding matrix.

The inclusion of oil introduces a new variable compared to previous studies. The addition of oil further enhances the effect of emulsifiers already present in the gluten-free flour composition [6], probably limiting the mobility of free charges and suppressing the contribution of dipolar relaxation processes to the imaginary part of complex permittivity. This results in overall lower dielectric constant values compared to gluten-containing flour. In particular, the presence of oil allows for a relaxation dispersion pattern similar to that observed in gluten-containing doughs [see Fig. 7(b)].

Despite this knowledge derived from the gluten-based bread doughs, the role, effects, and dielectric fingerprint that these

TABLE II
GLUTEN-FREE FLOURS USED IN THIS STUDY (FOR 100 G OF PRODUCT)

| Nutritional Components | Schar (g) | Il Molino (g) |
|------------------------|-----------|---------------|
| Fat | 0.7 | 0.3 |
| Carbohydrates | 82 | 83 |
| Fibers | 1.9 | 3 |
| Proteins | 3.3 | 2.3 |
| Salt | 0.75 | 0.1 |

TABLE III
FORMULATIONS OF THE GLUTEN-FREE DOUGHS

| Ingredients | Ref. Amount (g) | Range (g) | Percent Range (%) |
|-------------|-----------------|-----------|-------------------|
| Flour | 120 | Const. | Const. |
| Water | 68 | 65–68–70 | 54–56–58 |
| Oil | 12 | Const. | Const. |
| Salt | 1.5 | 0–1.5–2.5 | 0–1.25–2 |
| Yeast | 4 | 0–4–6 | 0–3–5 |

ingredients leaves on gluten-free doughs is unknown and demands for a specific investigation.

B. Sample Preparation

The gluten-free doughs analyzed in this study were prepared following a protocol similar to that used in previous research on gluten-containing Carasau bread doughs [10]. However, specific adaptations were made to account for the gluten-free nature of the doughs. To investigate the effects of gluten-free doughs composition on MW dielectric properties, for the two sets of commercial flours from *Schar* and *Il Molino*, different formulations were tested by varying the concentrations of water (W , in grams), salt (S , in grams), and yeast (Y , in grams) while keeping the amount of oil (O , in grams) and flour constant (F , in grams). *Schar* product, with properties reported in Table II, is composed of corn starch, rice flour, sorghum flour, rice starch, dextrose, vegetable fiber (psyllium), pea protein, hydroxypropyl methylcellulose as emulsifier, and salt. On the other hand, *Il Molino*, whose composition is reported in Table II, consists of corn starch, rice flour, tapioca starch, sugar, hydroxypropyl methylcellulose as emulsifier, and salt.

Using two products from *Schar* and *Il Molino* as primary ingredients, in this study, the experimental design included the variations in the concentration of W , Y , and S reported in Table III, so that 54 samples were prepared with varying compositions and then analyzed. Specifically, three possible values of each variable were tested, i.e., water (65, 68, and 70 g), salt (0, 1.5, and 2.5 g), and yeast (0, 4, and 6 g). A fixed amount of oil (12 g) and flour (120 g) were considered for all formulations, and the water temperature was set equal to 26 °C. Doughs were mixed manually at room temperature (22 °C) for 2–3 min. In particular, the flour was mixed with water, in which yeast and salt were dissolved, and then, oil was added.

C. MW Spectroscopy Characterization

For the 54 samples prepared for this study, the MW dielectric properties were measured using an OCP dielectric assessment kit (DAK 3.5, SPEAG, Zürich, Switzerland) probe, for a frequency range from 200 MHz to 4 GHz, connected to a vector network analyzer (VNA) Rohde & Schwarz ZNB26. The frequency range adopted in this study, compared to Table I, is relevant and covers the industrial, scientific, and medical bands of 0.915 and 2.45 GHz.

The OCP measurement system was calibrated using standard procedures (i.e., open, short, and load), and the temperature was monitored using a PT100 thermometer to ensure the reliability of results. Deionized water, with a temperature monitored to within ± 0.05 °C, was used as the load standard. The OCP was then positioned in direct contact with the sample to collect reflection coefficient data, which were converted into complex permittivity values using the DAK software.

Then, during measurements, the raw basic ingredients and the doughs were put in direct contact with the OCP, and ten measurements were taken. To ensure reliable results, ten measurements were performed for each sample, and the room experimental conditions (e.g., temperature and humidity) were carefully monitored. Error sources, including VNA noise and sample inhomogeneity, were addressed through calibration and statistical analysis.

The temperature of the doughs was ~ 26 °C. The dielectric response reflects the molecular interactions and water distribution within the dough, providing insights into the impact of composition. Indeed, OCP data acquire the complex permittivity $\varepsilon(f) = \varepsilon' - j\varepsilon''$, where ε' is the real part, which accounts for the electric energy stored in the sample material, and ε'' is the imaginary part, which accounts for conduction and polarization losses.

D. Mixing Formulas for Predicting MW Properties

Doughs, also for the gluten-free case, are complex heterogeneous materials, composed of flour, which is a mixture too, water, oil, salt, and yeast. It is possible to hypothesize that by knowing the dielectric response of ingredients from OCP measurements, the dielectric response of doughs could be predicted.

In this work, as done for the Carasau bread dough [10], we analyzed whether the homogenization equations could be applied to gluten-free doughs. The dielectric properties of gluten-free doughs were predicted using various mixing rules, which model effective permittivity based on the properties of individual components and their mass fractions.

1) *Maxwell–Garnett Formula*: The most used equation to homogenize dielectric media is the Maxwell–Garnett formula [34]. This relationship considers a background homogeneous medium with permittivity ε_b , in which a set of k dielectric spheres with permittivity ε_k is immersed, with f_k representing their mass fractions. Based on the polarizability of these spheres, the effective permittivity ε_d can be computed as [34]

$$\varepsilon_d = \varepsilon_b + 3\varepsilon_b \frac{\sum_{k=1}^K f_k \frac{\varepsilon_k - \varepsilon_b}{\varepsilon_k + 2\varepsilon_b}}{1 - \sum_{k=1}^K f_k \frac{\varepsilon_k - \varepsilon_b}{\varepsilon_k + 2\varepsilon_b}}. \quad (1)$$

The assumption—suitable for systems where one phase dominates—for the case of gluten-free doughs is that the flour forms the continuous matrix with dispersed inclusions of water, salt, yeast, and oil.

2) *Bruggeman Formula*: A more complicated approach is the Bruggeman formula [34], which considers the system as a symmetric mixture, accounting for mutual interactions between phases, so that the effective permittivity is found by solving the following equation:

$$\sum_{k=1}^K f_k \frac{\varepsilon_k - \varepsilon_d}{\varepsilon_k + 2\varepsilon_d} = 0. \quad (2)$$

3) *Lichtenecker Formula*: Another way of estimating the properties of a heterogeneous medium is to use the Lichtenecker formula and use a logarithmic combination to estimate the effective permittivity, well suited for systems with a wide range of permittivities [34]. In mathematical terms

$$\log \varepsilon_d = \sum_{k=1}^K f_k \log \varepsilon_k. \quad (3)$$

4) *Power-Law Formula*: A useful empirical model is the power-law formula [34]

$$\varepsilon_d^\beta = \sum_{k=1}^K f_k \varepsilon_k^\beta \quad (4)$$

where β is an adjustable parameter, introduced to account for the structural properties of the material.

Each mixing formula [see (1)–(4)] was applied to the OCP experimental data of the gluten-free dough, and their predictive accuracy over the frequency range of interest was evaluated by comparing calculated and measured permittivities.

E. Dielectric Spectroscopy Models

To model the dielectric response over the frequency range, different theoretical dielectric spectroscopy models were fitted to the data.

The modified multipole Debye model is defined as [10]

$$\varepsilon_{th}(\omega) = \varepsilon_\infty + \sum_{q=1}^{N_p} \frac{\Delta\varepsilon_q}{1 + j\omega\tau_q} + \frac{\sigma_{dc}}{j\omega\varepsilon_0} \quad (5)$$

where ε_∞ is the high-frequency permittivity, $\Delta\varepsilon_q$ is the dielectric strength, τ_q is the relaxation time, σ_{dc} is the static conductivity, and ε_0 is the vacuum permittivity.

The multipole Cole-Cole Model equation is [10]

$$\varepsilon_{th}(\omega) = \varepsilon_\infty + \sum_{q=1}^{N_p} \frac{\Delta\varepsilon_q}{(1 + (j\omega\tau_q)^{1-\gamma_q})^{\beta_q}} + \frac{\sigma_{dc}}{j\omega\varepsilon_0} \quad (6)$$

where γ_q is the so-called spreading or broadening parameter.

The Havriliak–Negami law is as follows [35]:

$$\varepsilon_{th}(\omega) = \varepsilon_\infty + \sum_{q=1}^{N_p} \frac{\Delta\varepsilon_q}{(1 + (j\omega\tau_q)^{1-\gamma_q})^{\beta_q}} + \frac{\sigma_{dc}}{j\omega\varepsilon_0} \quad (7)$$

where the parameter β is the symmetry parameter. For $\beta = 1$, (7) reduces to the Cole-Cole model [see (6)], whereas for $\beta = 1$ and $\gamma = 0$, (7) turns into the Debye equation [see (5)]. However, for $\beta = 1$ and $\alpha \neq 0$, (7) is again the Cole-Cole equation, but for $\beta \neq 1$ and $\alpha = 0$, (7) is called the Cole–Davidson equation. In this work, we will consider $N_p = 1$ for (7).

The fitting process employed the genetic algorithm routine written in MATLAB 2024a (The MathWorks Inc., Boston, MA, USA) and described in [10], [11], and [18]. In brief, the fitting routine selects an initial population of $N_{\text{ind}} = 3 \times 10^4$ individuals and then iterates ($N_{\text{iter}} = 500$), with a tolerance of 10^{-6} , to minimize the least-squares error between the measured and theoretical values, using a crossover probability of $P_c = 0.9$ and a mutation probability $P_m = 0.1$.

Each model's performance was assessed with a quality-related figure of merit [36], [37]. Therefore, the best model is found by comparing the percentage relative error ($\delta_\epsilon\%$) for both the real and imaginary parts of the permittivity considering the measured data (ϵ_m) and the theoretical ones (ϵ_t), i.e.,

$$\delta_\epsilon = \frac{|\epsilon_m - \epsilon_t|}{\epsilon_m} \times 100. \quad (8)$$

III. EXPERIMENTAL RESULTS

The goal of this work is to provide the first MW dielectric spectroscopy analysis of gluten-free bread doughs. To this aim, the ingredients, namely, two gluten-free commercial flours, water, salt, yeast, and olive oil, have been characterized using an OCP. Then, the possibility of predicting the doughs properties based on mixing formulas was assessed. The best dielectric spectroscopy model between Debye, Cole-Cole, and Havriliak–Negami models was found. The best model was then used to retrieve the fitting parameters for 54 different doughs prepared by varying the water, yeast, and salt content.

A. Ingredients Properties and Mixing Formulas

As a first step, the raw components of the gluten-free doughs were characterized. The real and imaginary parts of the relative dielectric permittivities of the starting ingredients are presented in Fig. 1. From Fig. 1, it can be observed that yeast and water have high dielectric permittivities and losses, whereas olive oil and gluten-free flours have similar dielectric permittivities. The oil has the lowest dielectric losses. Another relevant point is that the two commercial gluten-free flours have a very similar dielectric behavior. The obtained results are in relatively good agreement with those observed in previous studies on gluten-containing doughs [10].

From the knowledge of the dielectric spectra of individual ingredients, different mixing models [see (1)–(4)] were used to predict the dielectric spectra of a gluten-free bread dough ($W = 68$ g, $S = 1.5$ g, and $S = 4$ g), and the results are shown in Fig. 2. From Fig. 2(a), the real part of the dielectric permittivity of the gluten-free dough cannot be modeled by any mixing formulas, presenting a narrow overlap with the power-law model. In Fig. 2(b), the power-law model can partially predict the

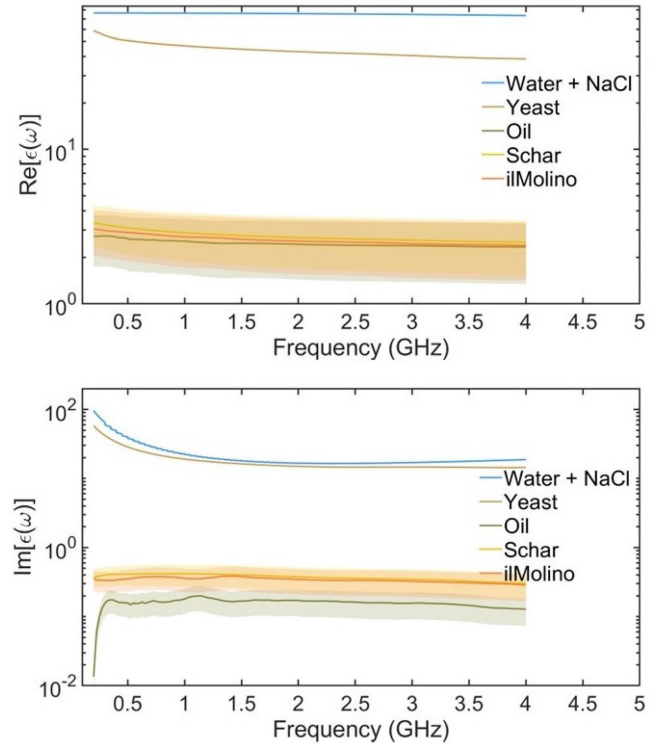


Fig. 1. (a) Real and (b) imaginary relative dielectric permittivities over frequency for the raw materials (saline, yeast, flour, and oil) used for dough preparation.

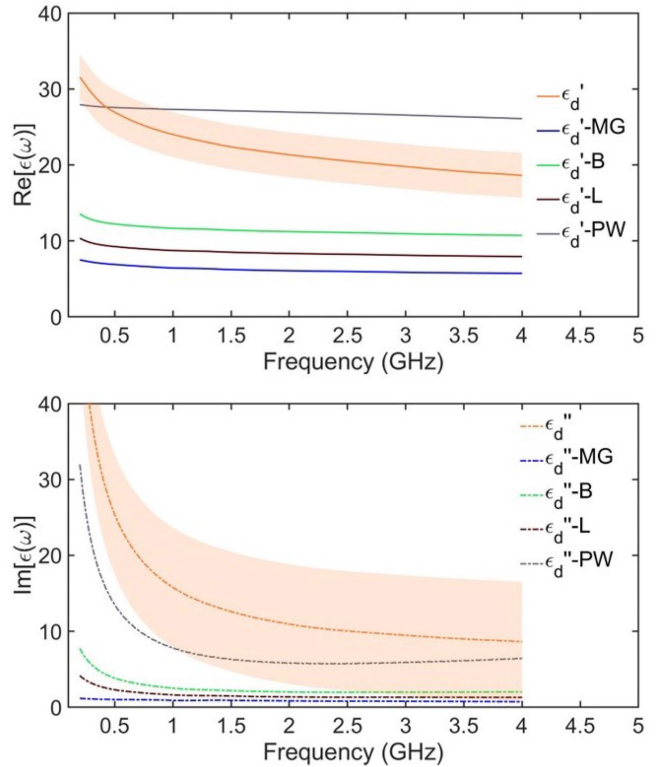


Fig. 2. (a) Real and (b) imaginary relative dielectric permittivities over frequency for the dough (*ilMolino* $W = 68$ g, $S = 1.5$ g, and $S = 4$ g case) compared to the predictions of the mixing models.

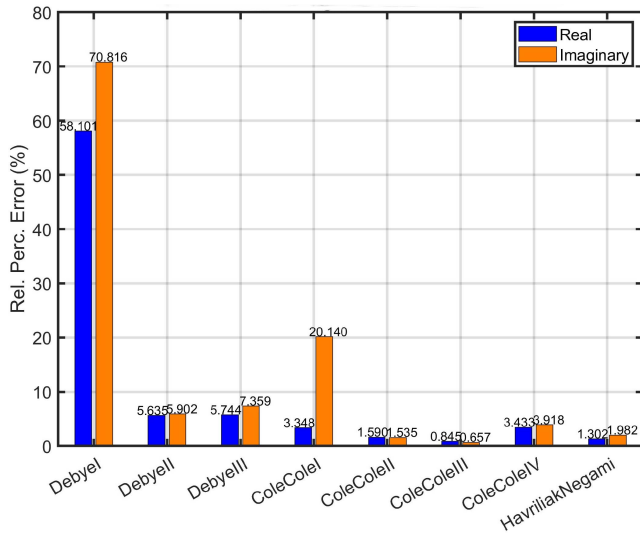


Fig. 3. Barplot for the relative percentage error for each model.

imaginary part of the gluten-free dough permittivity for $f > 1$ GHz, but, even though a similar slope can be recognized, the actual values are far from the average ε''_d values.

The findings from Fig. 2 clearly highlight that the mixing models cannot be used to predict the MW dielectric properties of gluten-free doughs starting from the individual components. Therefore, alternative dielectric spectroscopy strategies must be explored.

B. Best Dielectric Model

For accurate characterization, it is essential to adopt MW spectroscopic models that accurately describe the dielectric response of the dough. To interpret the measured dielectric spectra, a series of dielectric models have been applied, namely, Debye model with one, two, and three poles; the Cole-Cole model with one, two, three, and four poles, and a single-pole Havriliak–Negami model [see (5)–(7)]. The fitting procedure was carried out using a nonlinear optimization algorithm implemented in MATLAB, with the objective of minimizing the relative error between experimental data and model predictions. The model that produced the lowest relative percentage error was then selected and used in all subsequent modeling steps.

In order to select the best dielectric spectroscopy model for the dielectric response of gluten-free data, a reference dataset for fitting was chosen. We selected a gluten-free dough sample prepared with medium-level concentrations of all variables and ingredients, i.e., 68 g of water, 1.5 g of salt, and 4 g of yeast. Among the tested models, as can be seen in Fig. 3, the three-pole Cole-Cole model exhibited the lowest average error, on both ε' and ε'' , highlighting its suitability to describe the dielectric properties of gluten-free doughs. From Fig. 3, it is possible to notice that the single-pole Debye model results in very large errors ($\sim 65\%$), whereas the monopole Cole-Cole model has large errors on ε'' ($\sim 20\%$). By increasing the number of poles for Debye and Cole-Cole models, the errors δ_ε reduce up to three poles, whereas for a four-pole Cole-Cole model, the error increases up to $\sim 3.5\%$. Remarkably, the Havriliak–Negami

TABLE IV
THIRD-ORDER COLE-COLE PARAMETERS FOR VARYING WATER CONTENT (w), AND FIXED SALT ($s = 1.5$ g) AND YEAST ($y = 4$ g) CONTENT

| | 65 [g] | 68 [g] | 70 [g] |
|-----------------------|------------|------------|------------|
| ε_∞ | 3.5347 | 3.8897 | 4.6154 |
| $\Delta\varepsilon_1$ | 27.6886 | 23.6811 | 1.2749 |
| τ_1 (s) | 3.4087e-05 | 9.9999e-05 | 9.9999e-05 |
| γ_1 | 0.0436 | 0.7061 | 0.0546 |
| $\Delta\varepsilon_2$ | 45.1871 | 41.6403 | 9.2992 |
| τ_2 (s) | 5.3638e-07 | 5.1303e-07 | 1.5548e-07 |
| γ_2 | 0.5352 | 0.7218 | 0.7974 |
| $\Delta\varepsilon_3$ | 29.4819 | 27.1347 | 33.5862 |
| τ_3 (s) | 3.8691e-11 | 5.5209e-11 | 3.9428e-11 |
| γ_3 | 0.4578 | 0.5431 | 0.4961 |
| σ_{DC} (S/m) | 0.4687 | 0.4659 | 0.7066 |

TABLE V
THIRD-ORDER COLE-COLE PARAMETERS FOR VARYING YEAST CONTENT (y), AND FIXED SALT ($s = 1.5$ g) AND WATER ($w = 68$ g) CONTENT

| | 0 [g] | 4 [g] | 6 [g] |
|-----------------------|------------|------------|------------|
| ε_∞ | 5.0816 | 3.8897 | 2.5939 |
| $\Delta\varepsilon_1$ | 63.5383 | 23.6811 | 33.5094 |
| τ_1 (s) | 6.0195e-05 | 9.9999e-05 | 1.8990e-05 |
| γ_1 | 0.6403 | 0.7061 | 0.7865 |
| $\Delta\varepsilon_2$ | 19.8868 | 41.6403 | 47.9372 |
| τ_2 (s) | 6.5444e-07 | 5.1303e-07 | 2.5031e-07 |
| γ_2 | 0.2885 | 0.7218 | 0.5312 |
| $\Delta\varepsilon_3$ | 32.7007 | 27.1347 | 27.8715 |
| τ_3 (s) | 1.4862e-10 | 5.5209e-11 | 3.4907e-11 |
| γ_3 | 0.5711 | 0.5431 | 0.5350 |
| σ_{DC} (S/m) | 0.3169 | 0.4659 | 0.4258 |

TABLE VI
THIRD-ORDER COLE-COLE PARAMETERS FOR VARYING SALT CONTENT (s), AND FIXED YEAST ($y = 4$ g) AND WATER ($w = 68$ g) CONTENT

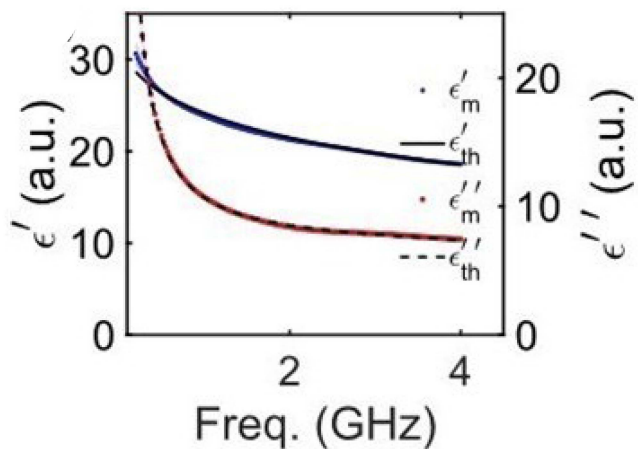
| | 0 [g] | 1.5 [g] | 2.5 [g] |
|-----------------------|------------|------------|------------|
| ε_∞ | 5.7611 | 3.8897 | 3.4175 |
| $\Delta\varepsilon_1$ | 47.1934 | 23.6811 | 31.8149 |
| τ_1 (s) | 1.0000e-04 | 9.9999e-05 | 4.5199e-05 |
| γ_1 | 0.0372 | 0.7061 | 0.8437 |
| $\Delta\varepsilon_2$ | 25.1698 | 41.6403 | 24.7262 |
| τ_2 (s) | 5.9316e-07 | 5.1303e-07 | 9.9999e-07 |
| γ_2 | 0.8004 | 0.7218 | 0.0296 |
| $\Delta\varepsilon_3$ | 20.3408 | 27.1347 | 34.2726 |
| τ_3 (s) | 3.5059e-11 | 5.5209e-11 | 1.0569e-10 |
| γ_3 | 0.3680 | 0.5431 | 0.5578 |
| σ_{DC} (S/m) | 0.3320 | 0.4659 | 0.7363 |

model has a very low average error that is comparable to the two-pole Cole-Cole model.

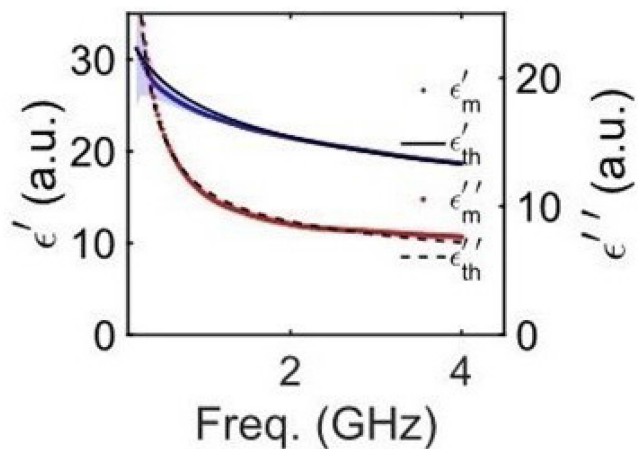
Anyway, the three-pole Cole-Cole model has the lowest average error ($\sim 0.7\%$), and it was identified as the most accurate. Consequently, the dielectric data from all the 54 gluten-free dough samples were fitted to this model.

C. Composition Influence on Dielectric Properties

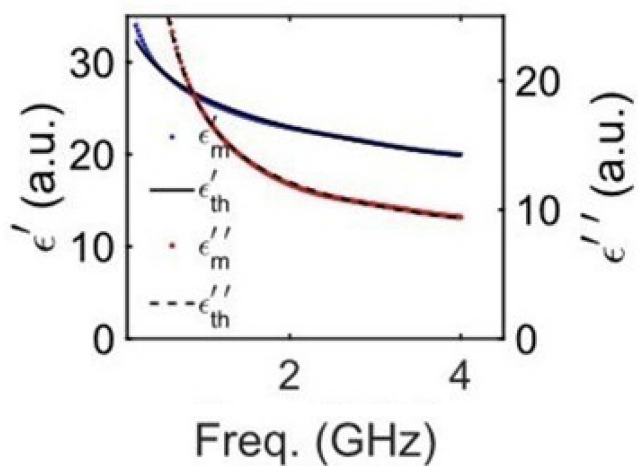
The parameters of the third-order Cole-Cole model were extracted for each formulation to evaluate the influence of composition on the dielectric behavior (see Tables IV–VI). For the characterization of the complete set of gluten-free doughs for the two used commercial flours, and to avoid introducing an excessive number of graphs and table in this article, herein a



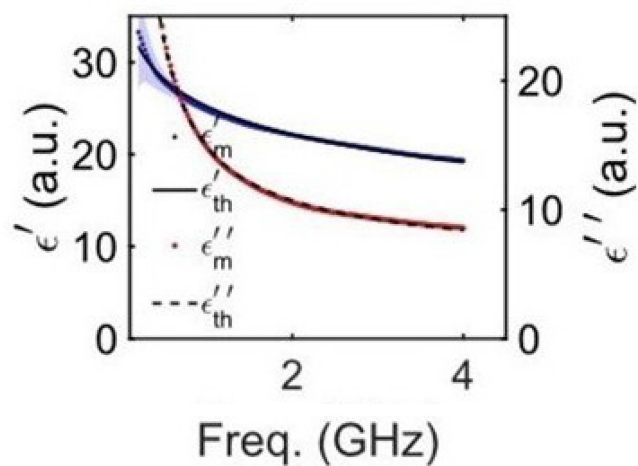
(a)



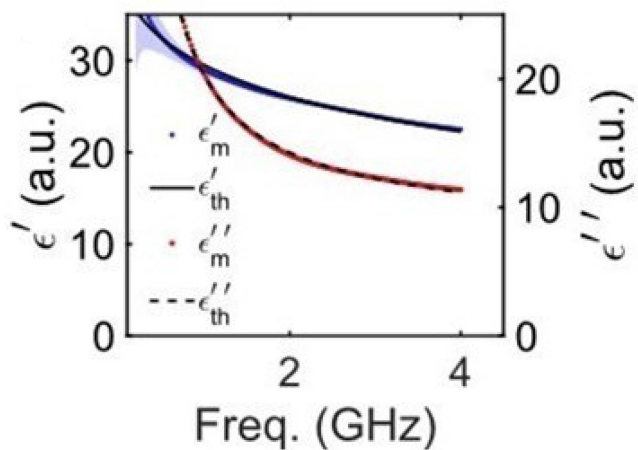
(a)



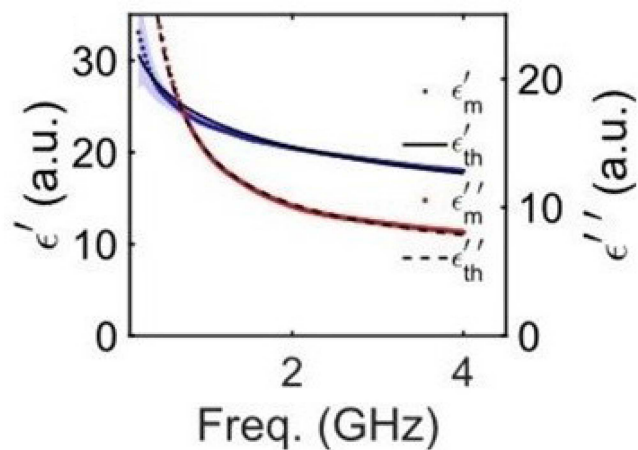
(b)



(b)



(c)



(c)

Fig. 4. Gluten-free dough made with *Schar* flour, with component contents of (a) $W = 65$ g, $Y = 0$ g, $S = 0$ g; (b) $W = 68$ g, $Y = 4$ g, $S = 1.5$ g; and (c) $W = 70$ g, $Y = 6$ g, $S = 2.5$ g (top to bottom).

Fig. 5. Gluten-free dough made with *ilMolino* flour, with component contents of (a) $W = 65$ g, $Y = 0$ g, $S = 0$ g; (b) $W = 68$ g, $Y = 4$ g, $S = 1.5$ g; and (c) $W = 70$ g, $Y = 6$ g, $S = 2.5$ g (top to bottom).

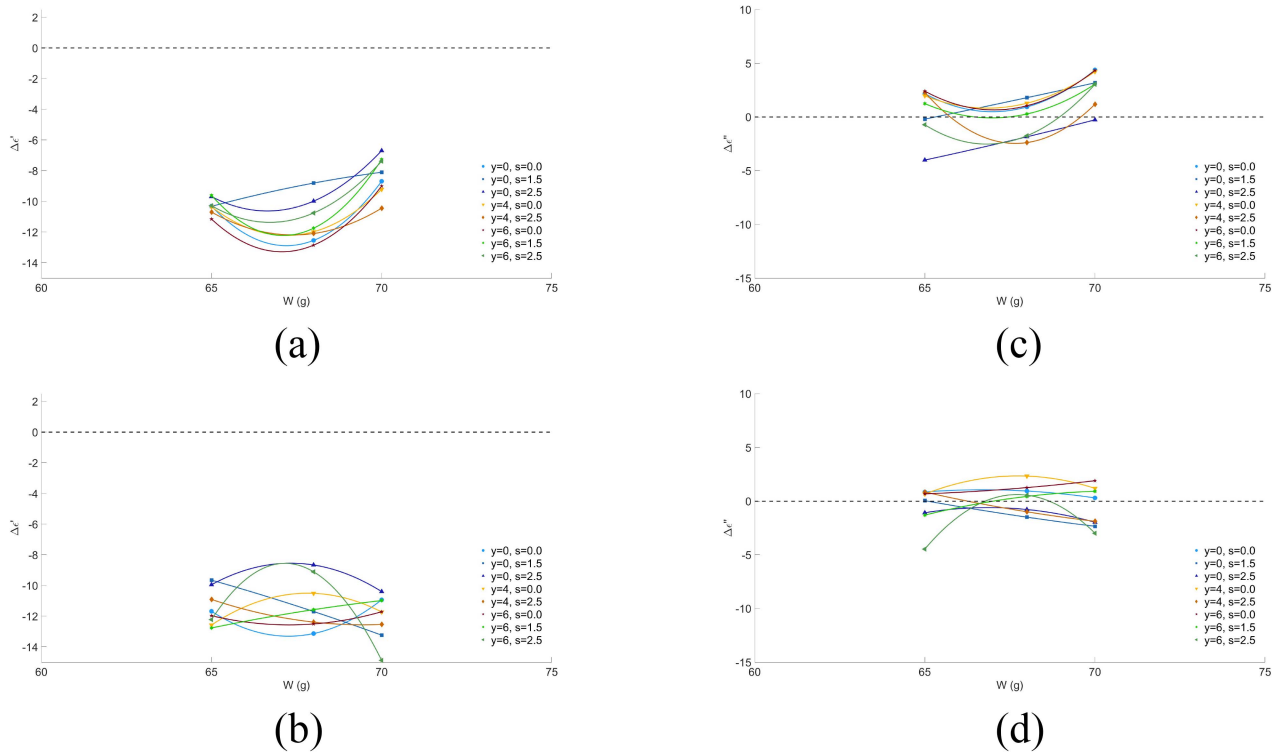


Fig. 6. Comparison of the relative difference of the dielectric permittivity at $f = 2.45$ GHz with respect to the reference case $W = 68$ g, $S = 1.5$ g, and $Y = 4$ g when varying the composition for ilMolino (a) and (c) and Shar (b) and (d).

selected, but exhaustive, set of results for both data gluten-free flours is reported. All other graphs and table reporting the fitting coefficients are given in the online supplementary material.

The results for the no salt and no yeast, reference dough and excess water, and salt and yeast cases are shown in Figs. 4 and 5. All the results (also in the supplementary material) report the combined standard deviation due to calibration, systematic error, and drift errors [36]. A larger uncertainty was found in the lower frequency range ($f < 1$ GHz) and for the *il Molino*-based doughs. Anyway, starting from dry, yeast-free, and salt-free doughs [see Figs. 4(a) and 5(a)], ϵ' lies in the range $\sim [30, 20]$, whereas ϵ'' ranges from ~ 25 to ~ 8 , for both flours, indicating a relevant strong dielectric and lossy behavior. As salt is introduced in the doughs, the slope of ϵ'' is changed and becomes steeper (see supplementary material). For the case of $Y = 0$ g and $S = 2.5$ g, the excess salt leads to noticeable differences in the morphology and pattern of ϵ'' between the *Schar* and *il Molino* doughs. Salt, due to its influence on ionic conduction, primarily affected ϵ'' at lower frequencies.

For what concerns the yeast contribution to the dielectric spectra, for $S = 0$ g, a slight decrease in ϵ' and ϵ'' can be observed from Figs. 4(b) and 5(b) (see supplementary material). As yeast increases to $Y = 6$ g, the $\epsilon'(f)$ shape is affected, suggesting that the polarization strength can be regulated by this component.

The critical results of the doughs revealed that water content (W) had the most significant impact on both ϵ' and ϵ'' , consistently with its role as the primary polar component, as can be noted from Figs. 4 and 5 and from the supplementary material.

The distinct nature of the two gluten-free flours, as reported in Table II, suggests that differing amounts of fats, fibers, and salt may account for the differences observed across the two doughs sets, despite similar values of water, salt, and yeast. By comparing Figs. 4 and 5, evident differences emerge when yeast and salt are introduced into the dough. Moreover, the presence of salt and yeast alters the slope of the ϵ'' trend curve compared to the case where these components are absent, confirming the sensitivity of this method to the presence of the components under investigation.

D. Trend Analysis of Dielectric Constant Differences

Finally, to further investigate the impact of composition variations on the dielectric properties of gluten-free doughs, the difference between the measured dielectric constant values of the reference dough ($W = 68$ g, $Y = 4$ g, and $S = 2.5$ g) and the measured values for all other samples has been analyzed. This analysis was performed for both the real (ϵ') and imaginary (ϵ'') parts of the dielectric constant, focusing on variations in water content, which is the most relevant component. Fig. 6 illustrates the differences in the dielectric constant values for the three water levels tested ($W = 65, 68, 70$ g). Although the range of variation is narrow, a nonlinear trend is observed for ϵ' at a fixed frequency of $f = 2.45$ GHz, confirming a relationship between water content and polarization behavior in the dough matrix. From Fig. 6(a), it can be noted that, with respect to the reference case, ϵ' decreases for any ingredient added or removed to and

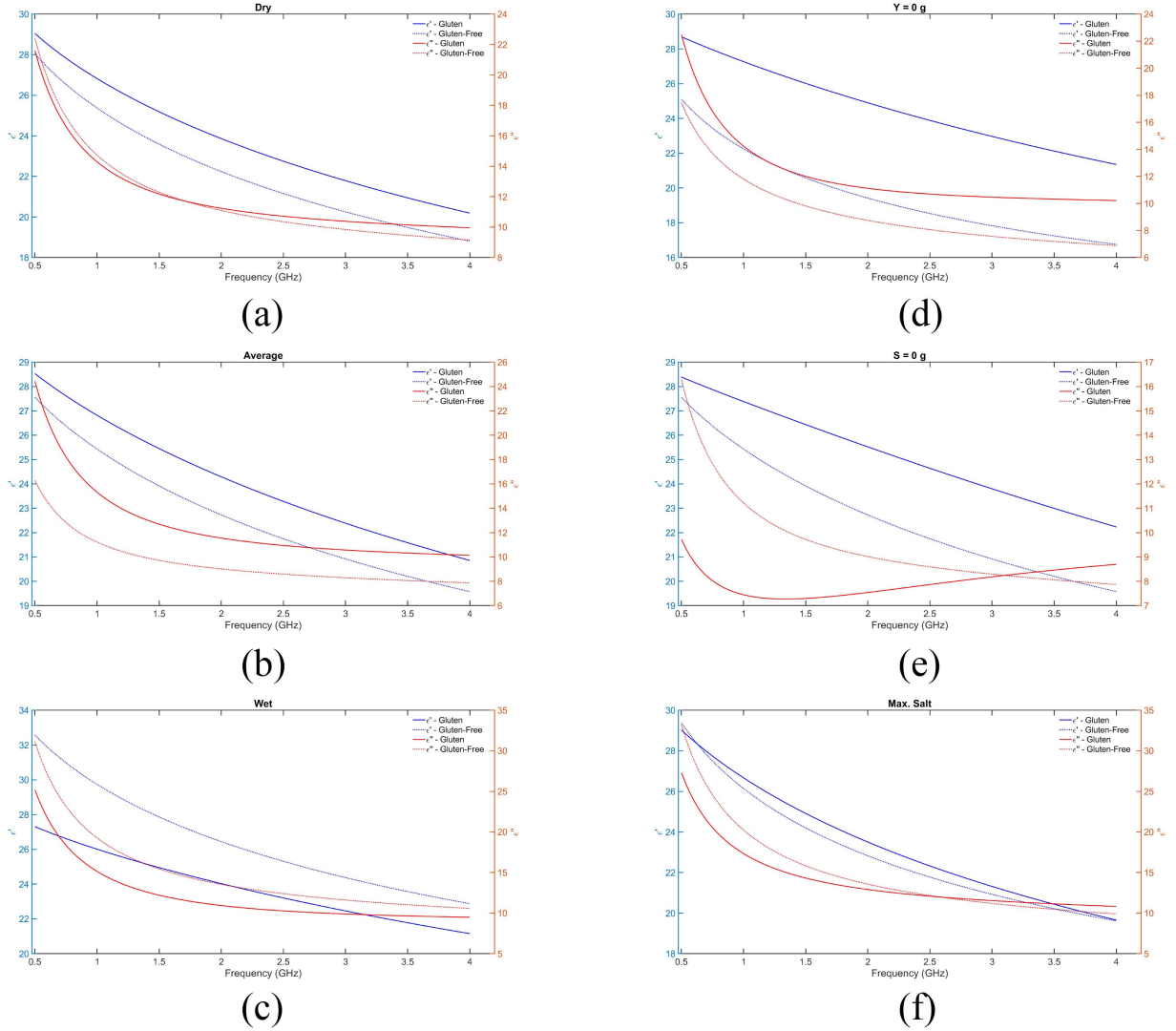


Fig. 7. Comparison of: (a) gluten dough $W = 46$ g, $Y = 1.5$ g, $S = 1.5$ g and gluten-free dough $W = 65$ g, $Y = 4$ g, $S = 1.5$ g; (b) gluten dough $W = 50$ g, $Y = 1.5$ g, $S = 1.5$ g and gluten-free dough $W = 68$ g, $Y = 4$ g, $S = 1.5$ g; (c) gluten dough $W = 54$ g, $Y = 1.5$ g, $S = 1.5$ g and gluten-free dough $W = 70$ g, $Y = 4$ g, $S = 1.5$ g; (d) gluten dough $W = 50$ g, $Y = 0$ g, $S = 1.5$ g and gluten-free dough $W = 68$ g, $Y = 0$ g, $S = 1.5$ g; (e) gluten dough $W = 50$ g, $Y = 1.5$ g, $S = 0$ g and gluten-free dough $W = 68$ g, $Y = 4$ g, $S = 0$ g; and (f) gluten dough $W = 50$ g, $Y = 1.5$ g, $S = 2.5$ g and gluten-free dough $W = 68$ g, $Y = 4$ g, $S = 2.5$ g.

from the doughs, for both *Shcar* and *il Molino*. However, no such trend is evident for ϵ'' , as can be noted from Fig. 6(b). This may be due not only to the more complex interplay between electrical conduction and relaxation processes, but also to the physical and biochemical roles of salt and yeast in doughs. Further studies are needed to correlate these spectra and variations to the microstructural and biochemical properties of gluten-free bread doughs.

E. Comparative Analysis With Gluten-Containing Doughs

The results obtained for gluten-free doughs were compared with those of previous studies on gluten-containing doughs from [10], [11], and [18]. Considering the most representative cases, the comparison is given in Fig. 7. Several key differences can be observed, which can be attributed to the absence of gluten, the use of different types of flour, variations in ingredient

concentrations, and the addition of oil in gluten-free formulations. In particular, the use of gluten-free flours results in slightly lower dielectric permittivity ($\sim [7, 18]\%$) values compared to the gluten-free case [10] (see Fig. 7). The slopes of $\epsilon''(f)$ are not identical, except for the doughs with average composition. The losses of gluten-free dough are lower (up to $\sim 20\%$) for the average and yeast-free cases [see Fig. 7(b) and (d)], but for dry, wet, and no salt or maximum salt cases, the ϵ'' values are higher in the gluten free doughs [see Fig. 7(a) and (c)–(f)]. It is remarkable that the slopes of the imaginary part of the permittivity are almost identical for the dry dough case [see Fig. 7(a)], whereas it is very similar for all other cases except for those in which the salt is greatly varying [see Fig. 7(e) and (f)]. These behaviors can be attributed to fact that the gluten-free flours are a mixture of different components (see Table II). Indeed, salt is blocked by yeast, inhibiting the Na^+ and Cl^- movement, thus decreasing losses, until the salt does not reach

the value $S = 2.5$ g. Furthermore, the presence of the emulsifier in the flours is able to bound water, thus increasing the water-bound levels and modifying the relaxation response, modifying the polarization, and enhancing the polarization losses, thus explaining the different slopes. Oil presence in the system further increases this effect, since it acts as an emulsifier. Therefore, the presence of emulsifiers in gluten-free flours, which tend to block the free charges, can reduce the dielectric response, thus explaining the lower ε'' values. Moreover, the addition of oil further enhances the effect of the emulsifiers, as oil acts as a stabilizing agent for the emulsifying components. This interaction limits the mobility of free water molecules and suppresses the contribution of dipolar relaxation processes to the imaginary part of the complex permittivity.

IV. CONCLUSION

In this study, we investigated for the first time, and in a systematic way, the dielectric properties of gluten-free doughs. To this aim, we analyzed the dielectric response of raw ingredients using an OCP in the frequency range $f \in [0.2, 4]$ GHz and then evaluated the feasibility of using mixing formulas to predict the gluten-free dough spectra. We found that homogenization formulas, such as Maxwell–Garnett, Bruggeman, Lichtenecker, and power-law approaches, are not able to predict the MW dielectric response of gluten-free dough in the frequency range of interest. Therefore, to provide a first and in-depth understanding, we tested the multipole Debye, Cole-Cole, and Havriliak–Negami dielectric models to assess their applicability to gluten-free doughs. We have identified the three-pole Cole-Cole model as the best dielectric model, resulting in an average relative percentage error of 0.84% and 0.65% on the real and imaginary parts, respectively. The three-pole Cole-Cole model was then used to fit the spectra of 54 doughs with variable water, yeast, and salt content, thus providing, for the first time, an MW spectroscopy framework to obtain the dielectric characterization of this material. We have found that salt increases dielectric losses, whereas yeast slightly affects the real part of dielectric permittivity, and that water has the main role in affecting gluten-free doughs properties. Furthermore, by comparing the dielectric spectra of gluten and gluten-free doughs, we have found relevant differences for dry, wet, yeast-free, and salt-free cases, but we found a similar dielectric spectrum for the reference dough composition, thus suggesting that MW dielectric spectroscopy could be used as a tool for characterizing this class of food material.

The methodology and findings of this study could be used to support the food processing of gluten-free bread doughs and to design innovative MW sensors for monitoring and testing product quality. In particular, the rapid, noninvasive, and nondestructive nature of MW dielectric measurements makes them highly attractive for industrial applications, especially in the agri-food sector. In this field, traditional quality control methods are often invasive, making tested products unsellable, and are typically applied to a limited number of samples rather than to the entire production. This leads to partial and potentially insufficient monitoring. By contrast, the proposed MW techniques

enable real-time contactless inspection of all products, ensuring both consistency and safety while overcoming the limitations of conventional methods.

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Luigi Di Michele (Member, IEEE) received the master's degree (summa cum laude) in telecommunication engineering from the University of Naples "Parthenope," Naples, Italy, in 2023. He is currently working toward the Ph.D. degree in electronic and computer engineering (with a focus on the formulation of models for solving inverse problems) with the University of Cagliari, Cagliari, Italy.

From February to September 2024, he was a Research Fellow with the Electromagnetic and Remote Sensing Laboratory, University of Naples "Parthenope" within the PRIN 2022 ECOMARE project. During this time, his research focused on developing advanced methodologies for observing macroplastic debris in marine environments using optical and radar remote sensing.



Matteo B. Lodi (Member, IEEE) received the bachelor's degree in biomedical engineering from the University of Cagliari, Cagliari, Italy, in 2016, the master's degree in biomedical engineering from the Politecnico di Torino, Turin, Italy, in 2018, and the Ph.D. (Hons.) degree in electronic engineering and computer science from the University of Cagliari, in 2022.

From 2022 to 2023, he was a Technologist with the Electromagnetic Group, University of Cagliari, where he is currently an Assistant Professor (Italian type-A, fixed-term). His research interests include the modeling of bioelectromagnetic phenomena, especially radio frequency and microwave hyperthermia treatment, the study, manufacturing, and synthesis of magnetic biomaterials for tissue engineering applications, and the use of microwaves for biotechnology and environmental applications while working in the design and characterization of antennas for space and wearable applications.



Giacomo Muntoni (Member, IEEE) received the bachelor's degree in electronic engineering, in 2010, the master's degree in telecommunication engineering, in 2015, and the Ph.D. degree in electronic engineering and computer science, in 2019, all from the University of Cagliari, Cagliari, Italy.

He is currently a Technologist with the Applied Electromagnetics Group, University of Cagliari. His research interests include design and characterization of antennas for biomedical and aerospace applications, microwave-based dielectric characterization of materials, 3-D printing of radio frequency components, and monitoring of the space debris environment in low Earth orbit with the sardinia radio telescope, in collaboration with the Cagliari Astronomical Observatory.



Andrea Melis received the bachelor's degree in biomedical engineering from the University of Cagliari, Cagliari, Italy, in 2017.

He is currently with the University of Cagliari, where he has worked as an Assistant Researcher. His research interests include electromagnetic modeling and development of radio frequency coils at low and high frequencies, especially for magnetic resonance imaging at high field, the design and realization of wireless sensor network systems for monitoring industrial processes, such as bread manufacturing, and intelligent transportation systems.



Federica Di Prima received the Graduate degree in biomedical engineering from the University of Cagliari, Cagliari, Italy, in 2015.

She is currently a Project Manager with the University of Cagliari. She worked on the following projects: AISAC, IAPC, Crunch Sunalle, and Unicarasau. Her research interests include the dielectric characterization of doughs.



Ferdinando Nunziata (Senior Member, IEEE) was born in Italy, in 1982. He received the B.Sc. and M.Sc. degrees (summa cum laude) in telecommunications engineering, in 2003 and 2005, respectively, and the Ph.D. degree in curriculum electromagnetic fields, in 2008, all from the Università degli Studi di Napoli “Parthenope,” Napoli, Italy.

Since 2010, he has been an Assistant Professor in electromagnetic fields with the Università degli Studi di Napoli “Parthenope.” Since 2013, he has been a Guest Professor with Shanghai Ocean University, Shanghai, China. His research interests include applied electromagnetics, including electromagnetic modeling, single- and multipolarization sea surface scattering, radar polarimetry, synthetic aperture radar sea oil slick and metallic target monitoring, spatial resolution enhancement techniques, and global navigation satellite system—reflectometry. He is the author/coauthor of about 30 peer-reviewed journal papers.

Dr. Nunziata was a recipient of the 2003 IEEE Geoscience and Remote Sensing South Italy Chapter Best Remote Sensing Thesis Award, the 2009 Sebetia-Ter International Award for his research activities in remote sensing, and the 2012 Latmiral Prize, provided by the Italian Society of Electromagnetics. He was in the Organizing Committee of the 2008, 2010, 2012, and 2014 IEEE Graduate of Last Decade (GOLD) Remote Sensing Conferences at the European Space Agency, Frascati, Italy, at the Italian Naval Academy, Livorno, Italy, at the National Research Council, Rome, Italy, and in Berlin, Germany, respectively. He was a Session Chair at 2008 and 2012 IEEE International Geoscience and Remote Sensing Symposia, held in Boston, MA, USA, and in Munich, Germany, respectively. He is a Young Professional (formerly GOLD) representative of the IEEE Geoscience and Remote Sensing Society AdCom and of the IEEE Italy Section.



Giuseppe Mazzarella (Life Member, IEEE) received the Laurea degree in electronic engineering and the Ph.D. degree in electronic engineering and computer science from the Università Federico II of Naples, Naples, Italy, in 1984 and 1989, respectively.

In 1990, he became an Assistant Professor with the Dipartimento di Ingegneria Elettronica, Università Federico II of Naples. Since 1992, he has been with the Dipartimento di Ingegneria Elettrica ed Elettronica, Università di Cagliari, Cagliari, Italy, first as an Associate Professor and then, since 2000, as

a Full Professor, teaching courses in electromagnetics, microwave, antennas, and remote sensing. He is the author (or a coauthor) of more than 100 articles in international journals and a reviewer for many electromagnetics journals. His research interests include the efficient design of large arrays of slots, power synthesis of array factor, with an emphasis on constraint inclusion, microwave holography techniques for the diagnosis of large reflector antennas, the use of evolutionary programming for the solution of inverse problems, in particular problems of synthesis of antennas and periodic structures, agrifood, and therapeutic applications of microwaves.



Alessandro Fanti (Senior Member, IEEE) received the Laurea degree in electronic engineering and the Ph.D. degree in electronic engineering and computer science from the University of Cagliari, Cagliari, Italy, in 2006 and 2012, respectively.

He is currently an Associate Professor of Electromagnetic with the Department of Electrical and Electronic Engineering, University of Cagliari. His research interests include the use of numerical techniques for mode computation of guiding structures, optimization techniques, analysis and design of waveguide slot arrays, analysis and design of patch antennas, radio propagation in urban environment, modeling of bioelectromagnetic phenomena, and microwave exposure systems for biotechnology and bioagriculture.

Dr. Fanti is a member of the IEEE Antennas and Propagation Society, the Italian Society of Electromagnetism, the National Interuniversity Consortium for Telecommunications, and the Interuniversity Center for the Interaction Between Electromagnetic Fields and Biosystems.