Effects of Carasau Dough Composition on the Microwave Dielectric Spectra up to 20 GHz

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***Abstract*—Carasau bread is a traditional product from Sardinia (IT). This flat bread is experiencing industrial advancement, through automation, and has great market potential. However, there is lack of understanding of how the composition (water content, salt, and yeast concentration) affects the product quality. In this work, a microwave dielectric spectroscopy study is performed to investigate how the composition of Carasau bread doughs influences the spectra of this food product up to 20 GHz. A third-order Cole–Cole model was used for the physical and quantitative understanding of the electromagnetic properties of this food product. Then, it has been studied how salt, yeast, and water variations affected the model parameters. This work could pave the route to the development of non-destructive, contactless microwave sensors for Carasau bread quality assessment.**

***Index Terms*—Bread doughs, Cole–Cole model, microwave (MW) spectroscopy.**

I. Introduction

FLAT breads (FBs) are an essential part of the daily diet in the Mediterranean area [1]. For countries such as Italy, France, Spain, Morocco, Algeria, Tunisia, Libya, Egypt, Jordan, Lebanon, Greece, Malta, and Croatia, FBs are cheap, convenient, and palatable food products. They are sometimes considered as street food, sometimes as a delicacy, but always embody history, tradition, and values. However, modifications in modern lifestyle and urbanization may cause FBs to disappear [1]. These local foods, with their short baking time, no use of tableware, water, and long-shelf life, are sustainable and potentially valuable products. Only 7% of them have industrial production, but a 1.77-fold increase in their market (from 81 796.6 to 145 180.9 M€) is expected in five years [1]. Therefore, valorizing and innovating FBs is necessary, and actions to prevent the reduction of biodiversity (see the European regulation no. 1151/2012) [2], while promoting activities and technical or nutritional improvement, are required.

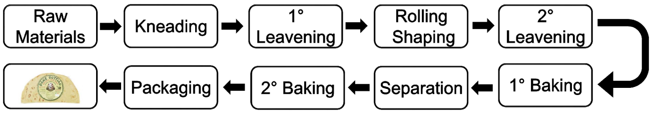

Fig. 1. Resume of Carasau bread manufacturing process.

In the mediterranean area, there are 143 FB types, 75 of which are from Italy, as a strong regional gastronomic difference exists in this territory [1]. Among these food products, Carasau bread is a traditional Sardinian FB that is experiencing a period of innovation, through industrialization and automation, and expansion [3], [4]. Carasau is a flat, golden-color, crisp and crunchy, double-layered, circular bread made of durum wheat remilled semolina, compressed bakers' yeast (*Saccharomyces cerevisiae*), iodized salt (NaCl), and water. The production process of Carasau bread is depicted in Fig. 1. It involves kneading of raw ingredients, a first leavening stage ($\sim$40 min), a sheeting, and two baking stages (for cooking temperatures $T_c > 300\,°C$) [5]. The product is then packaged and sold. The most critical events in determining the final product quality were identified to occur during the dough preparation and leavening. Therefore, most of the work about Carasau bread production focused on this point. However, since the Carasau bread production process is energy consuming and affected by wastage, automation and industrial advancement can increase its sustainability, while providing a unique control of the product quality.

To supply its production process with high-tech engineering solutions, wireless sensors networks were designed and tested for monitoring environmental parameters, such as temperature (T), relative humidity in air ($H_{\%}$), pressure, CO and CO$_2$ concentrations, or the machinery kinematic parameters [5], [6], [7], [8]. In [9], the possibility of using radiofrequency identification and near-field communication devices in combination with blockchain technology to certify and strengthen the supply chain and logistics was investigated. Recently, an image processing algorithm based on color-driven segmentation and support vector machine was developed to monitor and quantify the radii and eccentricity of Carasau dough sheets, before and

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after the second leavening [10]. However, given that Carasau bread industry aims to develop a quality scheme (it applies only to ∼60% of mediterranean FBs), other solutions are required to empower this productive process.

To this aim, a deep knowledge of the dough's parameters is required. Therefore, physical characterization methods were used. So far, rheological analyses were performed to characterize the dough [11], [12], [13]. Nuclear magnetic resonance studies [14] and indirect Fourier transform infrared spectroscopy [15] are methodologies used to assess Carasau bread dough quality and composition. These approaches, while effective, demand time-consuming and complicated sample preparation, are expensive, require cumbersome equipment, and necessitate expert interpretation of the results. Therefore, they are not suitable for developing cost-effective, easy-to-use devices. Consequently, there is a lack of characterization methodologies capable of seizing the essential features of the Carasau dough quality, and being easily translated into devices for this peculiar food industry.

In this work, microwave (MW) dielectric spectroscopy (DS) of Carasau bread dough is performed, by investigating, for the first time, the effects of composition, in terms of water weight (W), yeast (Y), and salt (NaCl) concentrations. The spectra of different samples will be measured, and then fitted into a model to investigate the effects on the parameters. The rest of this article is organized as follows. In Section II, the state of the art of MW DS for bread and doughs is given. In Section III, the methodological details about the dough preparation, the experimental setup, and the modeling procedure for the MW DS study are provided. The results are presented in Section IV and discussed in Section V. Finally, conclusions and future perspectives are given in Section VI.

II. STATE OF THE ART OF BREAD DOUGH DS

DS performed at MW frequencies ($f \in [300\text{ MHz}, 30\text{ ;GHz}]$) is a nondestructive, physical characterization methodology of value for studying food product properties [16], [17], [18]. This characterization methodology has already been applied to bread and dough. However, we will demonstrate that the methodologies and the findings are scarcely applicable to the case of Carasau bread dough, thus calling for a novel and unique characterization study.

In [19], the dielectric features of a commercial bread dough were investigated using an open-ended coaxial line, focusing on $f \in [0.6 - 2.45]$ GHz. The study considered normal, extra water, extra flour, as well as raw and baked conditions. However, the MW spectra was not modeled. In [20], a coaxial cell was used to study the attenuation and phase shift of dough made using commercial flour, varying salt and water content, for $f \in [0.3 - 6]$ GHz. The dielectric permittivity was not measured but studied indirectly, and therefore, no theoretical modeling was developed. In [21], an open-ended coaxial probe (OECP) was used to measure the complex dielectric permittivity of white bread for $f \in [0.1 - 1.8]$ GHz and $T \in [25, 85]$°C. Mixing and homogenization were studied through the Lichtenecker equation and the effective permittivity of white bread was modeled. Although a polynomial model was used to describe the dependence of the permittivity from fs, it was empirical and not physics based.

TABLE I
REMILLED DURUM WHEAT SEMOLINA CHARACTERISTICS

Component	Protein	Carbohydrates	Fats	Proteins	Gluten
Value	10%	70%	1%	11%	8%

From the analysis of the literature, it is evident that previous works on DS spectroscopy of bread doughs presented a restricted frequency range with reduced modeling [19], [20], [21]. Therefore, recent works dealt with the challenge of a deeper understanding of MW DS spectra of bread doughs. In particular, a broadband DS study was performed for $f \in [0.1\text{ Hz} -10\text{ MHz}]$, at cryogenic temperatures ($T \in [-135, 25]^\circ$ C), for Carasau loafs [22]. For this low-frequency range, a Havriliak-Negami model was used and the temperature dependence of the relaxation angular frequency was fitted to an Arrhenius-like model. Despite this radiofrequency DS approach could distinguish the carbohydrates contribution and identify the interaction between water and dough components, the low-temperature range is prohibitive. Therefore, in our previous work [23], we performed a DS investigation in the MW range, up to a maximum frequency $f = 8.5$ GHz, for Carasau doughs, in the case of a nominal composition of $W = 50\%$, $Y = 1.5\%$, NaCl $=$ 1.5%, considering different remilled durum wheat semolina batches and investigating the dynamic changes during the first leavening ($\Delta t = 40$ min). We observed that, as the leavening time increases, the static dielectric permittivity changes, and hence the entropy of the system diminished (i.e., $S \propto \frac{\partial \epsilon_s}{\partial T}$). In [23], the possibility of predicting the effective permittivity of the dough was investigated using different mixing formulas, but it was found that the homogenization equations hold for $f > 2.45$ GHz. However, in [23], the effects of composition on the MW permittivity spectra were not considered. In this work, we will further extend the frequency range up to 20 GHz and investigated, for the first time, the influence of the composition of Carasau bread on the complex dielectric permittivity.

III. METHODS

A. Bread Dough Preparation

The Carasau bread doughs were prepared using a commercial remilled durum wheat semolina, whose characteristics are reported in Table I. In this study, the weight of semolina (300 g) is used as a reference for the amount of other ingredients. As previously stated, the other ingredients used were distilled water, commercial baker yeast, and commercial iodized salt. The proportion and amount of these four ingredients typically used during Carasau bread production were considered. The water content W has been varied in the range $[46, 54]\%$, with a 4% interval, while the yeast (Y) and salt (NaCl) concentrations considered herein were 0%, 1.5% and 2.5%. A total of seven different Carasau doughs has been considered, as reported in Table II.

A Sana Smart Breadmaker (SANABMS, Sana S.r.o., CZR) machine is used for dough kneading (see Fig. 1). The kneading was carried out a room temperature (25 °C) and for 20 min.

TABLE II
COMPOSITION OF CARASAU DOUGHS

W (%)	Y (%)	$NaCl$ (%)
46	1.5	1.5
50	1.5	1.5
54	1.5	1.5
50	0	1.5
50	2.5	1.5
50	1.5	0
50	1.5	2.5

These mixing and stirring parameters are selected to replicate the conditions encountered in the industrial practice and to mimic other studies [11], [12], [13], [14], [15], [22].

B. DS Measurements

The response of a material to an electromagnetic field operating in the MW regime can be interpreted in terms of the complex permittivity [24], [25], [26]

$$\epsilon = \epsilon' - j\epsilon'' \tag{1}$$

where $\mathfrak{Re}(\epsilon) = \epsilon'$ is the real part or in-phase component, which accounts for the magnitude of the dipole moments of the material constituents and the stored energy. In (1), the term $\mathfrak{Im}(\epsilon) = \epsilon''$ is the imaginary part or out-of-phase component of the permittivity, which, in turn, accounts for the energy dissipated in the material. Through broadband MW measurements of ϵ, the different polarization and relaxation mechanisms, which can be ionic, orientational, and interfacial, can be visualized and investigated.

Since ϵ is the signature of microstructure and composition of the material under test (MUT), a remark is in order. The complex permittivity of a food material is a function of several variables. Most food materials are dispersive materials; and hence, an unknown function of f must be retrieved through theoretical modeling or empirical fitting [21], [23]. Furthermore, food materials are heterogeneous media, and their composition plays a key role in defining the microstructure and final properties. Therefore, in this work, we assume that the complex permittivity of Carasau doughs obeys to

$$\epsilon = \epsilon\,(f, W, Y, \text{NaCl}) \tag{2}$$

since T, $H_{\%}$, and P are monitored and kept constant during preparation and measurements [23]. Also, concerning [23], the dependence from the leavening time, t, is neglected and a single time point, the final leavening time, is considered. Our measurements aims to elucidate for the first time (2).

The MW DS investigation was carried out by using a 3.5 OECP dielectric assessment kit system (SPEAG,[1] operating at $f \in [200\text{ MHz}-20\text{ GHz}]$), connected to a Rhode & Schwarz ZNB20 vector network analyzer (VNA, operating for $f \in [100\text{ kHz}-20\text{ GHz}]$), for measuring the complex reflection coefficient at the OECP-material interface, from which ϵ is retrieved through a capacitive model [27], [28], [29]. The probe is connected to the VNA using a rigid, low-loss coaxial cable. The measurement system was calibrated following the open, short, and load procedure [30]. A 1 L deionized water was used as load while monitoring the solution temperature using a digital PT100 thermometer (±0.01 °C).

The MUT, in the form of a loaf, is placed below the probe. In total, ten measurements were recorded for each dough, after 40 min of leavening. In this work, the combined standard deviation has been considered which was obtained by summing the random uncertainty (∼2%), systematic uncertainty (0.1%–1.4%) and drift (0.1%–0.2%), as found in [31], by using $k = 2$ as coverage factor for a 95% confidence interval. The permittivity values are, therefore, represented with the expanded uncertainty. The average curves are reported and the total standard deviation of the measurements is added.

C. Modeling of the MW Spectra

The modeling of the MW dielectric spectra of Carasau bread dough, up to 8.5 GHz, was done using a multipole Cole–Cole model [23]. In [23], it was shown that the use of Debye and Havriliak–Negami equations resulted in large errors (up to ∼34%) and relevant discrepancies in the spectra trends. It has been shown that a nonresonant model such as the Cole–Cole one can describe the macroscopic behavior of complex systems, presenting non-exponential relaxation laws, such as food materials. In this work, it has been tested if the third-order Cole–Cole model from [23] can be extended to 20 GHz. Therefore, the dielectric permittivity of Carasau doughs (1) was modeled as

$$\epsilon = \epsilon_\infty + \sum_{i=1}^{N_p} \frac{\Delta\epsilon_i}{1 + (2\pi j f \tau_i)^{1-\gamma_i}} + \frac{\sigma_{\text{DC}}}{2\pi f \epsilon_0} \tag{3}$$

where ϵ_∞ is the relative permittivity at optical frequencies, N_p is the number of poles or the model order ($N_p \in \mathbb{Z}^+$), $\Delta\epsilon_i$ is the difference between the ith static relative permittivity and the optical one (i.e., $\Delta\epsilon_i = \epsilon_i - \epsilon_\infty$), τ_i is the ith relaxation time (in s), and, finally, σ_{DC} is the static electrical conductivity (in S/m), while ϵ_0 is the vacuum permittivity.

In (3), there are $2 + 3N_p$ parameters, which for $N_p = 3$ implies 11 unknowns for the three-poles Cole–Cole model. To retrieve these parameters, we used MATLAB 2021a (The MathWorks, Inc., USA). Briefly, using a genetic algorithm (GA), for all the N_F frequencies, the absolute difference between the experimental and theoretical permittivity values (ϵ_m and ϵ_{th}, respectively) for the vector of unknowns $\mathbf{x}$ has been minimized. In mathematical terms, the following equation was solved

$$F(\mathbf{x}) = \sqrt{\frac{1}{N_F} \sum_{q=1} N_F \left[\left| \frac{\epsilon'_m - \epsilon'_{\text{th}}}{\epsilon'_m} \right|^2 + \left| \frac{\epsilon''_m - \epsilon''_{\text{th}}}{\epsilon''_m} \right|^2 \right]}. \tag{4}$$

In (4), the theoretical permittivity is computed using (3), while ϵ_m is obtained from the OECP measurements. For the GA, the initial population size was $N_{\text{ind}} = 30000$ individuals, while we fixed the maximum iteration number to $N_{\text{iter}} = 500$. The Tournament selection method was used [32], [33], while the crossover and mutation probabilities were set to $P_C = 0.9$ and $P_M = 0.1$, respectively. The constraint tolerance was 10^{-6}.

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[1] [Online]. Available: www.speag.com

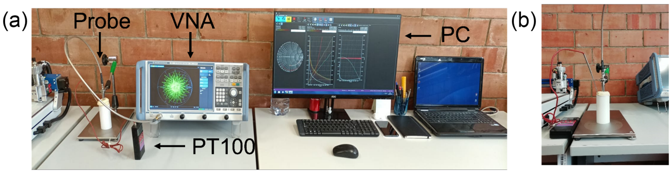

Fig. 2. (a) Measurement setup. (b) Details of the material under test during the OECP measurements.

To evaluate the quality of the fitting, a suitable figure of merit and error metric was selected, i.e., the relative percentage error between the measured values and the theoretical spectroscopy model, so that an error δ was computed for both the real and imaginary parts as follows:

$$\delta_{\epsilon'} = 100 \cdot \frac{\epsilon'_m - \epsilon'_{\text{th}}}{\epsilon'_m}\%$$

$$\delta_{\epsilon''} = 100 \cdot \frac{\epsilon''_m - \epsilon''_{\text{th}}}{\epsilon''_m}\%. \tag{5}$$

Given that (3) can account for the dielectric dispersion (i.e., $\epsilon(f)$), in order to study the influence of different dough composition on the MW response of Carasau loafs and quantitatively investigate (2), we performed the fitting procedure and derived the model parameters for all the samples and cases in Table II.

IV. RESULTS

The measured complex dielectric permittivity values for the different Carasau bread dough samples are given in Fig. 3.

In Fig. 3(b), (f), and (h), the dielectric spectra for the nominal composition of $W = 50\%$, NaCl $= 50\%$ and $Y = 1.5\%$ are reported. It can be noticed from Fig. 3(a) that, with respect from this situation, if no yeast is used (i.e., $Y = 0\%$, which reflects a case in which the operators forget to add this ingredient), the dielectric strength of the dough increases up to 30, for $f < 1$ GHz, while the imaginary part of the dielectric permittivity presents a nonmonotonically decreasing curve with a shoulder around 5.8 GHz. As the yeast concentration increases, both the real and imaginary parts of the permittivity decrease [see Fig. 3(b) and (c)].

For $Y = 1.5\%$, the variation of water content in the range $W \in [46, 50]\%$, the influence on the morphology of the dielectric spectra is lower. Indeed, the shape of the curves remains approximately the same, but the values of ϵ' and ϵ'' are strongly influenced by W. A drier dough [$W = 46\%$, Fig. 3(a)] present lower dielectric strength and losses. As the water amount increases, both ϵ' and ϵ'' increases. On average, it is possible to observe that ϵ'' increase by ~ 2 units per 2% of water weight percentage.

For a dough with $W = 50\%$ and $Y = 1.5\%$, if the salt concentration is varied, some significant modifications in the MW response of Carasau dough can be observed. In particular, in the absence of salt, the spectra drastically changes, as can be observed in Fig. 3(g). Indeed, the ϵ' curve can reach higher values (up to ~30) in the lower frequency bound, changing steepness with respect to Fig. 3(h). The most relevant difference in the dielectric spectra is the occurrence of a resonant response and in the appearance of peaks for ϵ'' [see Fig. 3(g)]. The maximum is occurring at $\sim f = 7.2$ GHz. However, as NaCl increases, ϵ'' return to a decreasing function of f. For NaCl $= 2\%$, it can be noticed that the dielectric strength and losses are highest, as can be seen in Fig. 3(i).

TABLE III
THIRD-ORDER COLE–COLE PARAMETERS FOR VARYING WATER CONTENT (W), AND FOR FIXED SALT AND YEAST (NACL $= 1.5\%$, $Y = 1.5\%$)

	$W = 46\%$	$W = 50\%$	$W = 54\%$
ϵ_∞	1.59	2.30	2.58
$\Delta\epsilon_1$	39.43 ± 0.10	26.46 ± 3.66	20.40 ± 2.40
τ_1 (μs)	49.20	67.30	59.3
γ_1	0.25	0.62	0.48
$\Delta\epsilon_2$	40.75 ± 10.09	8.90 ± 0.04	18.69 ± 5.59
τ_2 (μs)	0.77	0.35	0.43
γ_2	0.52	0.05	0.42
$\Delta\epsilon_3$	30.75 ± 2.19	28.89 ± 1.28	26.5 ± 0.93
τ_3 (ps)	23.71	20.00	15.11
γ_3	0.40	0.36	0.34
σ_{DC} (S/m)	0.47 ± 0.04	0.58 ± 0.02	0.62 ± 0.03
$\delta_{\epsilon'}$ (%)	0.63	1.26	1.57
$\delta_{\epsilon''}$ (%)	0.95	1.41	1.96

TABLE IV
THIRD-ORDER COLE–COLE PARAMETERS FOR VARYING SALT CONCENTRATION (NACL), AND FOR FIXED WATER AMOUNT AND YEAST ($W = 50\%$, $Y = 1.5\%$)

	$NaCl = 0\%$	$NaCl = 1.5\%$	$NaCl = 2\%$
ϵ_∞	4.7	2.30	1.56
$\Delta\epsilon_1$	35.4 ± 3.8	26.46 ± 3.66	48.61 ± 0.00
τ_1 (μs)	9.06	67.30	93.50
γ_1	0.60	0.62	0.13
$\Delta\epsilon_2$	50.83 ± 7.37	8.90 ± 0.04	7.83 ± 0.00
τ_2 (μs)	0.40	0.35	45.52
γ_2	0.22	0.05	0.03
$\Delta\epsilon_3$	24.17 ± 1.54	28.89 ± 1.28	32.36 ± 2.08
τ_3 (ps)	18.5	20.00	28.8
γ_3	0.20	0.36	0.41
σ_{DC} (S/m)	0.20 ± 0.01	0.58 ± 0.02	0.63 ± 0.07
$\delta_{\epsilon'}$ (%)	1.48	1.26	1.19
$\delta_{\epsilon''}$ (%)	1.85	1.41	1.97

These considerations hold for the values and morphologies of ϵ' and ϵ'' curves. However, the spectra are not enough for understanding completely the MW response of this complex, dynamic and heterogeneous food materials. Therefore, the analysis has been refined and the data were fitted to a third-order Cole–Cole model, as explained in Section III-B. The $3 \cdot N + 2$ parameters have been retrieved for the seven investigated cases. The findings are reported in Tables III–V. In terms of model parameters, the water variation results in an increase in ϵ_∞ and σ_{DC}, as can be noticed from Table III, while the static dielectric permittivities $\Delta\epsilon_i$ and relaxation times τ_i $(i = 1, 2, 3)$ decreases. The broadening parameter γ_1 presents a nonlinear variation with W. In all cases, the fitting relative percentage errors for the real and imaginary parts are below 2%.

When the salt concentration in the Carasau bread doughs varies, it is possible to notice that the permittivity at optical frequency ϵ_∞ decreases by 30% for a 2% NaCl change. While the static permittivity of the first pole ($\Delta\epsilon_1 = \epsilon_{s,1} - \epsilon_\infty$) varies nonlinearly with NaCl, the first relaxation time τ_1 increases with

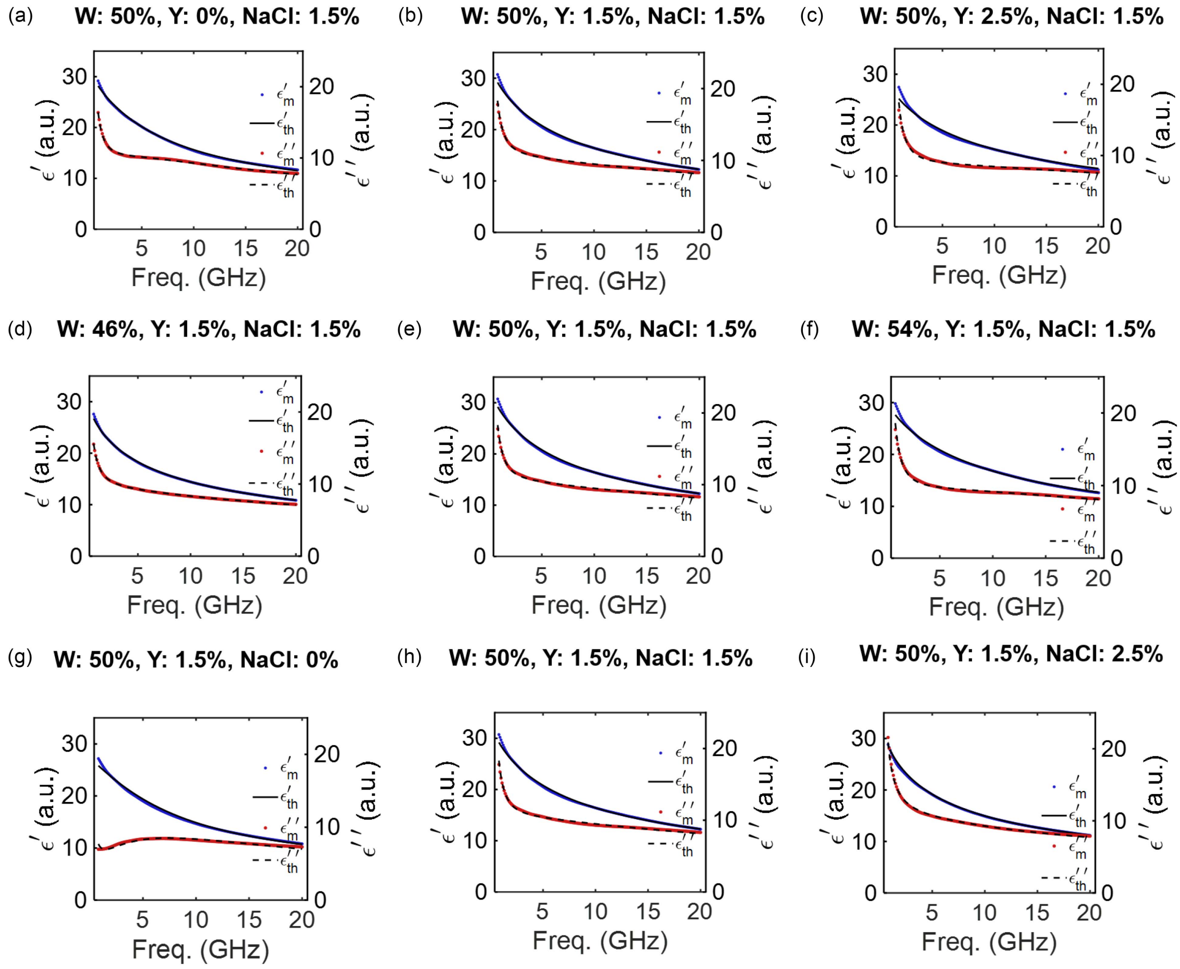

Fig. 3. Real and imaginary parts of the complex dielectric permittivity for: (a) $W = 50\%$, $Y = 0\%$, NaCl $= 1.5\%$, (b) $W = 50\%$, $Y = 1.5\%$, NaCl $= 1.5\%$, (c) $W = 50\%$, $Y = 2.5\%$, NaCl $= 1.5\%$, (d) $W = 46\%$, $Y = 1.5\%$, NaCl $= 1.5\%$, (e) $W = 50\%$, $Y = 1.5\%$, NaCl $= 1.5\%$, (f) $W = 54\%$, $Y = 1.5\%$, NaCl $= 1.5\%$, (g) $W = 50\%$, $Y = 1.5\%$, NaCl $= 0\%$, (h) $W = 50\%$, $Y = 1.5\%$, NaCl $= 1.5\%$, (i) $W = 50\%$, $Y = 1.5\%$, NaCl $= 2.5\%$ (a.u. = arbitrary units).

TABLE V
THIRD-ORDER COLE–COLE PARAMETERS FOR VARYING YEAST CONCENTRATION (Y), AND FOR FIXED WATER AMOUNT AND SALT ($W = 50\%$, NACL $= 1.5\%$)

	$Y = 0\%$	$Y = 1.5\%$	$Y = 2\%$
ϵ_∞	3.85	2.30	1.53
$\Delta\epsilon_1$	37.02 ± 0.03	26.46 ± 3.66	28.10 ± 0.04
τ_1 (μs)	59.10	67.30	53.24
γ_1	0.23	0.62	0.10
$\Delta\epsilon_2$	33.34 ± 9.92	8.90 ± 0.04	40.95 ± 6.00
τ_2 (μs)	65.8	0.35	0.09
γ_2	0.45	0.05	0.06
$\Delta\epsilon_3$	26.79 ± 0.76	28.89 ± 1.28	25.04 ± 1.15
τ_3 (ps)	20.9	20.00	14.72
γ_3	0.29	0.36	0.35
σ_{DC} (S/m)	0.54 ± 0.02	0.58 ± 0.02	0.58 ± 0.03
$\delta_{\epsilon'}$ (%)	0.81	1.26	0.45
$\delta_{\epsilon''}$ (%)	0.75	1.41	0.75

the salt content ($\sim$ ten times for a 2% NaCl). As regards the $\Delta\epsilon_2$, a strong reduction is observed from Table IV, while $\tau 2$ exhibits a drastic increase for increasing ionic content. Similar behavior is noticed for $\Delta\epsilon_3$ and τ_3. The variations of the γ_i parameters are different and seem to not follow a precise rule. Finally, as NaCl increases, the static electrical conductivity σ_{DC} increases, as expected.

For the pastry prepared by varying the yeast amount, as can be observed from Table V, ϵ_∞ decreases of about a third for a 2% variation. The first Cole–Cole pole is more affected by the yeast concentration. In particular, $\Delta\epsilon_1$, τ_1, and γ_1 vary nonlinearly, together with $\Delta\epsilon_2$. The second relaxation time τ_2 drastically reduces by ~ 2 orders of magnitude as Y increases. For increasing yeast concentration, γ_2 tends to zero, resulting in Debye-like responses for this pole. On the other hand, $\Delta\epsilon_3$, τ_3, γ_3, and σ_{DC} are poorly affected by Y variations. Finally, it is worth underlining that the fitting errors are very low (see Table V).

V. DISCUSSION

Given these findings, it is fundamental to provide an interpretation by comparing them with previous work on MW DS of bread doughs, especially Carasau, and to analyze these findings by using the knowledge derived from other characterization techniques.

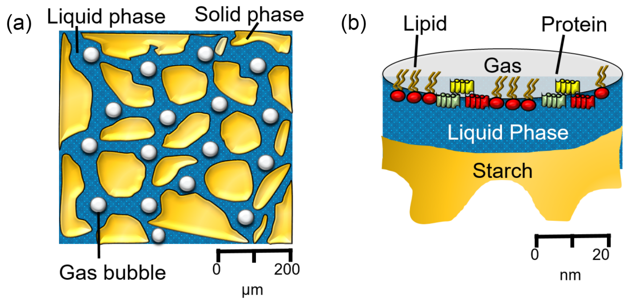

Fig. 4. Pictorial sketches of (a) microstructure of the Carasau bread dough and (b) nanostructure of the dough.

For any bread production, but mostly for FBs, such as Carasau, a critical factor is the dough water quantity (W). Indeed, leavening and cooking steps are strongly influenced by W [1]. The polar H_2O molecules act as a solvent and medium, as sketched in Fig. 4(a). In this liquid phase, chemical and biochemical reactions can take place. Water also regulates the interaction with the hydrophobic gluten elements [see Fig. 4(b)]. The gluten–water interactions are weaker than starch–water interactions [11]. When unhydrated, the gluten is characterized by β-sheets (39%) and random conformations (30%) [15]. It is known that as W increases, viscosity decreases [12]. From the thermogravimetric analysis of Carasau doughs, primary and secondary mass losses are observed through exothermic peaks, whose area under the curve and temperature, are associated with the water content [34]. The β-sheets and random conformations are converted into β-turns when the gluten gets hydrated and when the dough develops [15]. As humidity increases, the α-helix content increases since the number of hydrogen bonds in the gluten is reduced. From MW DS perspective, W acts directly on the dielectric strengths and losses [see Fig. 3(a)–(c)], since the polarization mechanisms modify. When W increases above 50%, the dough 3-D network is not able to completely absorb water [14]. As the bulk water content augments, the mobility of H_2O molecules also increases. In Table III, we observed that the ϵ_∞ and σ_{DC} increase. The higher values of $\Delta\epsilon_i$ for drier doughs ($W = 46\%$) can be explained by considering that a higher gluten content strengthens the network, which can incorporate more starch and absorb more water molecules [14].

As regards the salt, it provides a characteristic taste to the bread, but it strongly affects the dough's physical properties. Indeed, an NaCl addition is known to result in an increases in the mixing resistance, and dough extensibility, while decreasing stickiness and stabilizing the yeast fermentation rate, with a final improvement of bread texture [11], [12], [34]. In the dough liquid phase (see Fig. 4), the anions interact with the protein's positive charges, eliminating the repulsion among the gluten chains. Therefore, since the glass transition temperature decreases [34], the gluten microstructure is less hydrated, the protein strands elongate and the mechanical strength is higher [13]. The NaCl concentration can increase the dough optimal mixing time [12], [13]. From the dielectric MW spectroscopy point of view, all these considerations strongly reflects in the results shown in Fig. 3(d)–(f). The resonant behavior observed in Fig. 3(d), when NaCl $= 0\%$, is evidence that the gluten network is not assembled and structured in a normal way. As a matter of fact, the Cole–Cole model parameters reported in Table IV frames this behavior. In fact, as the salt content increases, the ionic free charges results in additional dissipation, as epitomized by an enhanced electrical conductivity.

Considering the variation of yeast (Y), i.e., the main actor in leavening, it is known that an addiction results in a viscosity reduction, and higher deformability [12]. Indeed, yeast can facilitate the incorporation of polysaccharides and proteins. As per the dielectric permittivity, as Y increases, and ϵ_∞, $\Delta\epsilon_1$, and τ_2 decrease. This behavior can be explained by the fact that fermentation takes place, causing CO_2 production, and hence, air bubbles are forming, thus lowering the effective permittivity of the dough [23]. The modified relaxation times (τ_1 and τ_3) account for a different microstructure, which reflects a different starch crystallization. During leavening glycerol, ethanol, succinic acid, and glutathione are releases. All these metabolites, which can influence the final product quality and flavor attributes, can modify the dielectric properties of the dough. More studies are required to link MW spectra with these features.

VI. CONCLUSION

In this work, the MW dielectric spectra of Carasau bread doughs of different composition have been investigated. Major lacks in the modeling, upper frequency bound, and understanding of the effects of bread ingredients have been found. Through complex dielectric permittivity measurement, a third-order Cole–Cole model was used to interpret the MW spectra of Carasau doughs for different water contents, salt, and yeast concentrations. The findings show that from the knowledge of the complex dielectric permittivity, it would be possible to extract and derive information about the composition, the microstructure, and indirectly the quality of this traditional food product from Sardinia (IT). With an in depth discussion, in particular, from the presented MW DS investigation, it has been confirmed that the water amount should be $W \in [50, 55]\%$ to avoid a negative impact on the dough structure [14]. As regards the amount of salt, a strict control procedure must be developed. Also, the yeast concentration should be minimized to optimize the leavening time and control the final bread properties.

The presented MW DS investigation represents a unique step for the development of innovative MW devices for empowering and supporting the flourishing industry of Carasau bread. The presented methodology and data could be useful for the optimization of double ridge waveguide sensors, manufactured in 3D-printing fused deposition modeling technology for the measurement of the complex permittivity of Carasau bread pastries [35], or antenna arrays for the in-line measurement of the water content in Carasau bread sheets [36].

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