Mathematical modelling of dielectric properties of food with respect to moisture content using adapted water activity equations

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Abstract

There is currently no recognised equation, or set of equations, that can be used to adequately describe moisture dependant dielectrics. This study addresses this issue so that moisture dependant dielectric properties can be directly input into drying models, where the microwave or radio frequency source is always limited to a single frequency. This was achieved by adapting water activity equations to describe the moisture dependant behaviour of the loss factor and the dielectric constant of hygroscopic inhomogeneous materials at microwave and radio frequencies. These equations were fitted to thirty moisture dependant loss factor and dielectric constant data sets. The adapted water activity equations proved to be very effective at describing dielectric behaviour, with the best equation fits to the thirty moisture dependant dielectric data sets having an average Mean Relative Error of 2.99%. The suitability of the equations are discussed, and specific equations are recommended for fitting to different types of moisture dependant dielectric response.

1. Introduction

Drying is a common industrial process. In the food industry in particular, almost every food product is dried at least once at one point of its preparation (Sokhansanj and Jayas, 2006). Microwave drying can be advantageous as microwave heating is direct, volumetric, instantaneous, easily controllable and fully electrified. However, microwave drying is a complex procedure, and the distribution of heating can be uneven if the process is not properly designed (Chandrasekaran et al., 2013). It is therefore desirable to model the microwave heating process for the purposes of optimisation. The dielectric response of foods affects their heating rate and the uniformity of the heating, when subject to Radio Frequency (RF) or microwave radiation.

Dielectric properties are moisture, frequency, and temperature dependant (Nelson and Datta, 2001). Currently there is not a generally accepted equation that describes dielectric properties of hygroscopic materials with respect to moisture content. This is especially true for inhomogeneous hygroscopic materials such as food. Previous studies have attempted to build predictive models, however these models had limitations when applied to foods due to the complexity of water and salt interaction with food constituents (Mudgett et al., 1980, 1977; Prakash et al., 1992; Sipahioglu and Barringer, 2003; Sun et al., 1995; To et al., 1974). There has been a recent increase in multiphysics modelling using Finite Element Analysis with fully coupled RF and heat transfer physics (Aversa et al., 2007; Chen et al., 2006; Datta, 2007; Dinčov et al., 2004; Ni et al., 1999; Renshaw, 2009) to determine the heating of food materials during RF or microwave processes. Such analysis is typically carried out at a single frequency in the Industrial Scientific and Medical (ISM) band, for which the applicator is specifically designed. Selection of the ISM frequency is typically done by taking into consideration the process requirements and the dielectric properties of the materials to be heated.

Modern multiphysics analysis seeks to optimise certain parameters such as power applied, applicator geometry, feed rate, and packing density of the dielectric load. These parameters are optimised to achieve maximum energy coupling to the dielectric load, sufficient headroom from arcing, production goals, and to be able to assess moisture levelling effects. Moisture levelling occurs most effectively when there is free water present in the food. Volumes within the food that have more free water will have a higher loss factor, and will be heated more readily by the microwave energy than drier regions that have a lower loss factor. Moisture levelling is less pronounced at lower moisture contents as the moisture is predominantly bound. The transition from bound water to free water can be observed by the transition from a relatively flat loss factor profile, to a rise in loss factor with respect to moisture content (Renshaw et al., 2019). The bound water is characterised by its isosteric heat, which must be released for further dehydration to occur (Wang and Brennan, 1991). When correctly utilised, microwave/RF moisture levelling improves moisture distribution, maximises energy efficiency, and reduces charring and other undesirable effects. Optimisation of microwave drying processes using modelling techniques saves time and cost when compared to using a trial and error approach with physical equipment that is iterated. However, current modelling of RF and microwave processes is hampered as it requires input of moisture dependant dielectric properties, which is typically not available as mathematical expressions. It would be extremely advantageous to have a general equation capable of describing experimental moisture dependant dielectric data for use in such studies.

Hygroscopic materials exhibit different sorption behaviour, which was classed into 5 different types by Brunauer et al. (1940). The type II isotherm (sigmoid shaped) is the most common isotherm observed for foods (Yanniotis and Blahovec, 2009). Renshaw et al. (2019) established that the relationship between moisture content and loss factor in food has the same sigmoid shape as the type II isotherm shape between moisture content and water activity. An exception occurs when salt dilution causes $d\varepsilon''/dM_{wb}$ to become negative at very high moisture contents for some foods, causing a deviation from the sigmoid shape, where ε'' is the loss factor, and M_{wb} is the wet basis moisture content. This occurs at 0.66kg.kg^{-1} wet basis for both potato and wheat flour (Kim et al., 1998; Mudgett et al., 1980), and can be attributed to dilution of salts causing a reduction in ionic conduction loss mechanisms.

There are numerous models describing sorption isotherm behaviour (Al-Muhtaseb et al., 2002), while there is a real lack of models describing moisture dependent dielectric behaviour. Considering there is now an established relationship between sorption isotherms and moisture dependant dielectric response (Renshaw et al., 2019), the aim of this study is to adapt established sorption isotherm models in order to accurately describe in an empirical way moisture dependant dielectric behaviour. These empirical models can then be used in multiphysics microwave/RF drying models to optimise industrial processes.

2. Method

Water behaviour in hygroscopic material can be complex, especially in food, where there are a number of substances that interact with water, such as sugars, salts, protein and starch (Asbi and Baianu, 1986; Chinachoti and Steinberg, 1984; Pollio et al., 1987; Starzak and Mathlouthi, 2006). Hence, a large number of water activity models have been developed to describe hygroscopic behaviour (Al-Muhtaseb et al., 2002). Common water activity equations were adapted in the present study to describe the moisture dependant behaviour of the loss factor and the dielectric constant. The GAB, Oswin, Henderson, Chung-Pfost, Chen, and Ferro-Fontan water activity equations were adapted as shown in Table 1 (Anderson, 1946; Chen, 1971; Chung and Pfost, 1967; De Boer, 1953; Ferro-Fontan et al., 1982; Guggenheim, 1966; Henderson, 1952; Oswin, 1946). They were selected on the basis that they are some of the most successful equations at describing sorption isotherms (Al-Muhtaseb et al., 2002; Iglesias and Chirife, 1995; Kaymak-Ertekin and Gedik, 2004; Moreira et al., 2010; Wang and Brennan, 1991).

One of the most commonly used water activity equations is the GAB (Guggenheim, Anderson and de Boer) equation, which is a kinematic model, where the parameters have real physical meaning and was independently derived by Guggenheim (Guggenheim, 1966), Anderson

(Anderson, 1946), and de Boer (De Boer, 1953) (Rizvi, 2005). It is used to fit sorption isotherms for a wide variety of foods and can provide good fits for the entire water activity range (Al-Muhtaseb et al., 2002; Kaymak-Ertekin and Gedik, 2004; Kiranoudis et al., 1993). The GAB equation is presented below, where a_w is water activity, M_0 is the monolayer, C relates to the difference in enphalpy between mono-layer and multi-layer sorption, and K relates to the differing heat of condensation of water and heat of sorption of a multi-molecular layer (McMinn and Magee, 1999). Hence it is a three parameter water activity equation.

$$M_{db} = \frac{M_0 C K a_w}{(1 - K a_w)[1 - K a_w + C K a_w]} \tag{1}$$

The GAB equation can be re-arranged in quadratic form as shown below:

$$a_w^2 (M_{db} K^2 - M_{db} K^2 C) + a_w (M_{db} K C - 2 M_{db} K - M_0 K C) + M_{db} = 0$$

Water activity can then be made the subject using the general quadratic equation shown below:

$$a_w = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{2}$$

Substituting the re-arranged GAB equation parameters into the quadratic Eq. 2 yields the following relationship:

$$a_w = \frac{1}{2}\left(\frac{-2M_{db} + M_{db}C - M_0 C + \sqrt{4M_{db}CM_0 + C^2 M_{db}^2 - 2M_{db}M_0C^2 + M_0^2C^2}}{M_{db}K(C-1)}\right)$$

As the sigmoid trend of water activity with respect to moisture content is generally the same as loss factor with respect to moisture content (Renshaw et al., 2019), the water activity term can simply be replaced with the loss factor. However, unlike water activity, the loss factor does not equal zero at zero moisture content. Therefore another term, ε_{om}'' is added, which is the loss factor at zero moisture content. The equation for loss factor is expressed in terms of moisture content wet basis as the trend is a more typical sigmoid shape when expressed in terms of wet basis rather than dry basis. The modified expression is shown in Eq. 3.

$$\varepsilon'' = \frac{1}{2}\left(\frac{-2M_{wb} + M_{wb}C - M_0 C + \sqrt{4M_{wb}CM_0 + C^2 M_{wb}^2 - 2M_{wb}M_0C^2 + M_0^2C^2}}{M_{wb}K(C-1)}\right) + \varepsilon_{0m}'' \tag{3}$$

However, this equation does not express the fall in loss factor which can be caused by dilution of the salts at high moisture contents i.e. when $d\varepsilon''/dM_{wb}$, becomes negative. To express this phenomenon, an extra term is proposed as shown in Eq. 4, where *U* and *S* are additional fitting parameters. This additional term can generate a sharp decrease in loss factor that only affects the expression during the relevant moisture content range. In instances where $d\varepsilon''/dM_{wb}$ does not turn negative, *U* returns to zero.

$$\varepsilon'' = \frac{1}{2}\left(\frac{-2M_{wb} + M_{wb}C - M_0C + \sqrt{4M_{wb}CM_0 + C^2M_{wb}^2 - 2M_{wb}M_0C^2 + M_0^2C^2}}{M_{wb}K(C-1)}\right) + \varepsilon''_{0m} - UM_{wb}^S \tag{4}$$

Other water activity equations can be adapted for loss factor using a similar approach. Some water activity equations are only suitable for returning values up to 1, as the maximum value for water activity is 1. In these instances, the adapted equation has to be factored up for loss factor using an additional parameter.

The proposed adaptions of water activity equations for loss factor can also be applied to the dielectric constant, as presented in Table 1. The equations for dielectric constant are however, generally less complicated. There is typically no need for the additional term used to describe a fall in loss factor. The dielectric constant always increases with moisture content, making it easier for the water activity equation to adequately describe its moisture dependence. However, there can be some instances where the additional parameters *U* and *S* can be useful to improve the fit when there is sharp levelling off of dielectric constant at high moisture content. In the vast majority of cases *U* returns to zero when using the equations in Table 1 to fit the dielectric constant to experimental data. Moisture dependant behaviour of the dielectric constant is less complex than loss factor and it is easier to fit a mathematical description. Hence most of the discussion in the study focuses on the mathematical description of dielectric loss. The only terms that have physical meaning in the proposed equations are the loss factor/dielectric constant ($\varepsilon''/\varepsilon'$), water activity ($a_w$), the wet basis moisture content (M_{wb}), and the loss factor/dielectric constant at zero moisture content ($\varepsilon_{om}''/\varepsilon_{om}'$). All other terms in the proposed equations presented in Table 1 are fitting parameters.

These proposed equations are intended to be used to fit experimental moisture dependant dielectric responses using non-linear regression at a single frequency. Therefore, the equations are independent of the physics of the dielectric response (i.e. whether dipolar rotation or ionic conduction is dominant), and depend on the adapted water activity equation's ability to fit the dielectric response at a particular frequency. The proposed equations do not contain temperature dependence, only moisture dependence for a given frequency. The loss factor may either increase or decrease with increasing temperature, depending on whether the operating frequency is higher or lower than the relaxation frequency. The equations can be further modified to include temperature dependence in future studies.

The moisture dependant dielectric loss factor equations presented in Table 1 were fitted to the measured moisture dependant loss factor of eight foods: Potato (3GHz at 25°C, wheat flour (27MHz at 22°C), chickpea flour (27MHz at 20°C and 90°C, 1.8GHz at 20°C and 90°C), yellow dent field corn (20MHz at 24°C), carboxymethyl cellulose (CMC) (2.45GHz at 20°C), hard red winter wheat (28MHz, 100MHz, 1GHz, and 12.1GHz at 24°C), apples (915MHz and 2.45GHz at 60°C) and grapes (2.45GHz at 25°C). The dielectric and sorption behaviour is discussed in detail by the prior study by Renshaw et al. (2019) and the method of measurement is shown in Table 2. The materials chosen were restricted to eight foods due to the lack of published moisture dependant dielectric data. However, the dataset does contain an interesting range of low sugar foods with high hydrocolloid content, and fruits that are high in sugar. The best two adapted equations were then used in its dielectric constant form, and were fitted to the measured moisture dependant dielectric constant for the same eight foods. The measured dielectric data was taken from literature, and the sources are shown in Table 2. The best fit was calculated using non-linear regression where the fitting criteria used was the residual sum of squares, which is described as follows:

$$RSS = \sum \left(u_e - u_p\right)^2 \tag{5}$$

Where u_e is the experimental value, and u_p is the value predicted by the model. The non-linear regression was carried out using Minitab 16 software (Minitab Inc., Pennsylvania State University, USA), which is a statistical analysis software package. This is the same approach as is used for fitting water activity equations to sorption isotherms. When undertaking a non-linear regression, it is always useful to have a good starting point. The best fit results presented in this study can be used as starting points for future studies when assessing similar moisture dependant dielectrics. Although not the case in this study, fitting parameters can also be iterated manually if software is not available. The Residual Sum of Squares is an effective way at determining the best equation fit for a given set of data, but it cannot be used to compare the fit of different data sets as the RSS figure is dependent on the number of data points. The Mean Relative Error (MRE) is useful for comparing equation fits of different data sets and is presented in Eq. 6.

$$MRE = \frac{100}{N} \sum \left| \frac{u_e - u_p}{u_e} \right| \tag{6}$$

It is generally understood that a good fit is obtained when MRE<10% (McLaughlin and Magee, 1998; McMinn et al., 2007).

3. Results

The parameters used to obtain the best fits to the experimental data are presented in Tables 4-7 for loss factor, and Tables 8-11 for dielectric constant. For each experimental data set the best equation fits are highlighted in bold.

The best fit equation for each moisture dependent loss factor curve analysed using RRS is presented in Table 3. Table 3 also presents the average MRE for all the equation fits, and the lowest MRE fit for each moisture dependent loss factor curve. The average best MRE fits for the 15 moisture depenent loss factor curves was 3.16%. The average best MRE fits for the 15 dielectric constant curves was 1.89%, making an overall average best MRE fit of 2.99% for the thirty moisture dependant dielectric data sets assessed. The fitting results for the adapted water activity equations are extremely satisfactory when considering that an MRE of less than 10% is deemed to be a good fit (McLaughlin and Magee, 1998; McMinn et al., 2007)

Looking in more detail at the loss factor fit results in Table 3, it can be seen that the average MRE of the adapted water activity equations is below 10% for all experimental data sets apart from wheat flour, which had an average MRE of 20.6% for the 6 equatoins used, and a best fit MRE of 13.9%. The wheat flour dataset is shown in Fig. 1a, each point plotted represents individual measurements rather than an average, this results in a disproportionate error in curve fitting. There were two sets of data containing a fall in ε'' with respect to moisture content, wheat flour and potato, the best fits of these are shown in Fig. 1a and 1b respectively. Each datapoint for potato shown in Fig. 1b represents duplicate measurements (standard deviations were were not presented by Mudgett et al. (1980)), and the best fit MRE achieved was 7.5%. Experimenal data plots containing negative $d\varepsilon''/dM_{wb}$ were more difficult to fit due to the extra parameters involved in the non-linear regression analysis, and had the highest MRE. It is difficult to ascertain whether the comparatively worse MRE experienced for potato and wheat flour is due to limitations in the equations ability to fit, the spread in experimental data points, or due to computation limitations of the non-linear regression.

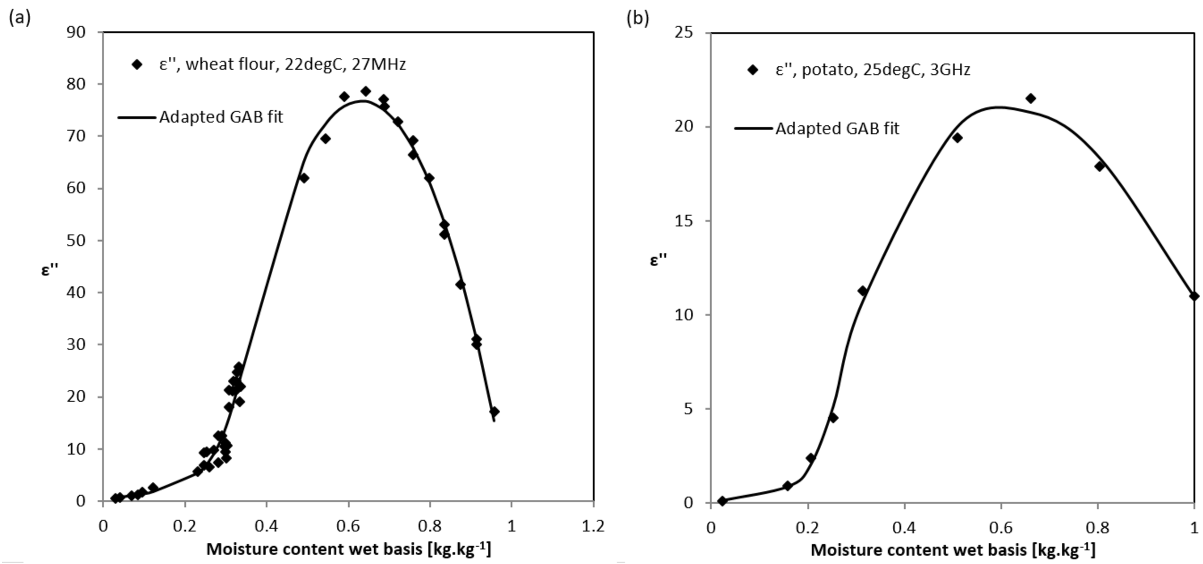

Fig. 1 Best fit RSS and MRE for (a) wheat flour loss factor measured by Kim et al. (1998) at 22°C, 27MHz using adapted GAB equation where each point is an individual measurement, and (b) potato loss factor measured by Mudgett et al. (1980) at 25°C, 3GHz using adapted GAB equation where each point is an average of duplicate measurements (no standard deviation presented by Mudgett et al. (1980))

Table 3 shows that the adapted Ferro-Fontan equation had the largest number of RSS best fits for the loss factor data analysed, followed by the adapted GAB equation. It is interesting to note that both the Ferro-Fontan and the GAB equation are derived kinematic models, where the parameters of the orignal water activity equaitons have real physical meaning. Out of the 6 adapted water activity equations analysed for loss factor, 5 different equations were best fits using RSS, and 5 equations had best fits using MRE. All 6 equations had at least one best fit when considering both RSS and MRE. A large number of sorption isothem equations exist because no one equation gives accurate results throughout the whole range of water activities, and for all types of foods (Al-Muhtaseb et al., 2002). As both water activity and loss factor is dependant on water mobility, which is dictated by the complex interaction of the water with the food matrix, it stands to reason that both water activity and loss factor require a number of equations to accurately describe the moisture dependant behaviour.

The equation fits that do not have to describe a negative $d\varepsilon''/dM_{wb}$ are excellent, with a minimum MRE best fit of $4.81\text{x}10^{-4}$ %. An Example of an equation fit to dielectric measurements that does not contain a negative $d\varepsilon''/dM_{wb}$ is shown in Fig. 2. The equation fits were also excellent for loss factor measurements that contained decreasing $d\varepsilon''/dM_{wb}$ to the point at which it reached zero, as shown in Fig. 3 where the MRE is 2.06% and 3.16% for Fig. 3a and 3b respectively. Error bars shown in Fig. 2 represent the standard deviation in loss factor for 21 samples (Nelson, 1979). Error bars in Fig. 3 represent the standard deviation of 5 samples at moisture contents over 0.224kg.kg^{-1} wet basis, and 13 to 16 samples at moisture contents below 0.224kg.kg^{-1} wet basis (Feng et al., 2002).

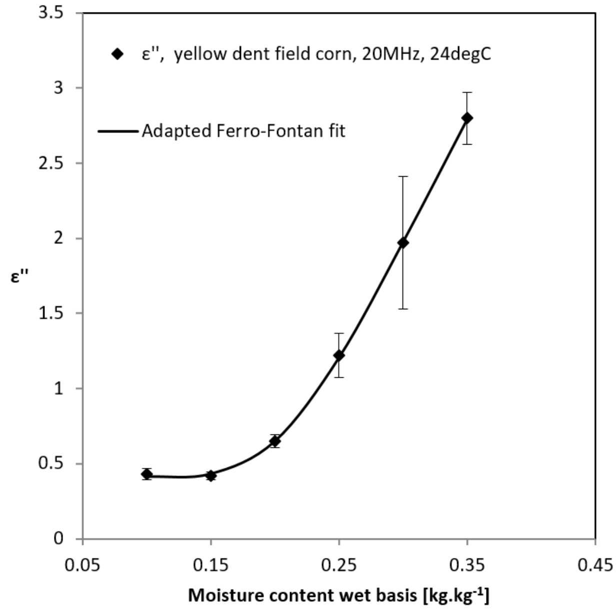

Fig. 2 Adapted Ferro-Fontan equation best fit MRE and RSS for yellow dent field corn at 20MHz, 24^{o}C, using loss factor measured by Nelson (1979) where each point is an average of 21 measurements

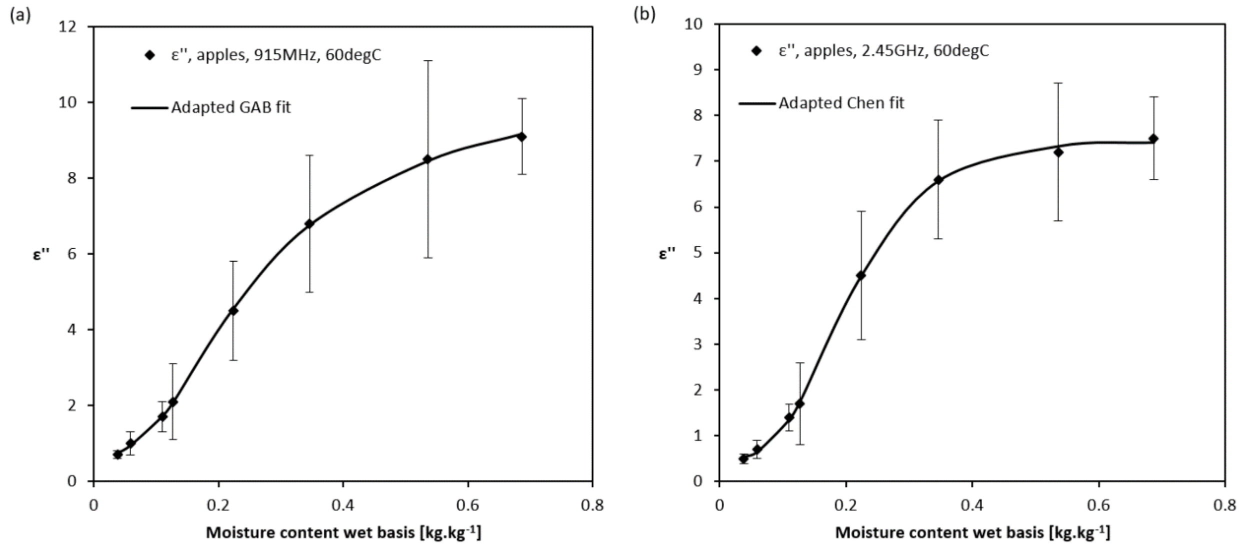

Fig. 3 Best fit RSS for apples at 60^{o}C using loss factor measured by Feng et al. (2002) at frequencies of (a) 915MHz (adapted GAB fit) and (b) 2.45GHz (adapted Chen fit) where each point is an average of 5 measurements above a moisture content of 0.23kg.kg^{-1} wet basis, and 13-16 measurements below 0.23kg.kg^{-1} wet basis

It can be seen from the dielectric constant equation fitting results presented in Tables 8-11 that a best fit MRE of less than 8% was achieved for each data set. For all dielectric constant data sets analysed, the additional mathematical term containing parameters U and S was not required, making the non-linear regression fitting relatively straight forward in each instance. The average best fit MRE for dielectric constant was 1.89%.

It can be seen in Table 12 that the adapted Chen equation preformed the best overall with an MRE of 4.2% for the 15 loss factor curves, showing that it is a good general equation to use for describing moisture dependant loss factor. The adapted GAB and Henderson equations preform best in instances where a reduction in loss factor with respect to moisture content was observed, or when the rate of change of loss factor with respect to moisture content approached zero. The fitting parameters U and S need to be utilised to describe this type of behaviour. The results showed that the adapted Ferro-Fontan equation should be used in instances where the monolayer/multilayer loss factor was very flat, followed by a sharp rise in loss factor. The choice of equation is therefore driven by the shape of the dielectric response rather than by the frequency, material, temperature, or magnitudes. The shape of the dielectric response is of course driven by the physics. The recommended application of the proposed equations is shown in Fig. 4 for the main types of loss factor profile with respect to moisture content. This application is descried with respect to the physics as follows:

Fig. 4(a): The adapted Chen equation can be used to represent a typical dielectric loss response, which is a gentle rise followed by a point of inflection that leads to a steeper rise. This point of inflection is due to either the transition from monolayer to multilayer, or the transition from multilayer to solution.

Fig. 4(b): The adapted Ferro-Fontan equation is most suitable when the loss factor behaviour at moisture contents below the first point of inflection is very flat with respect to moisture content, due to tightly bound moisture.

Fig. 4(c): The adapted GAB and Henderson equations are most suitable when the dielectric response is complicated by a decrease with respect to moisture content. This is typically seen when capillary condensation occurs at higher moisture contents so that the water behaves more like a solution (above 0.6kg.kg^{-1} wet basis for foods like potato and wheat flour), causing dilution of the salts and reduced ionic conduction loss contribution.

This recommendation applies for fitting equations to both moisture dependant loss factor and dielectric constant profiles. It is highly likely that the equations proposed in this study could be used for other dielectric materials, not just for foods.

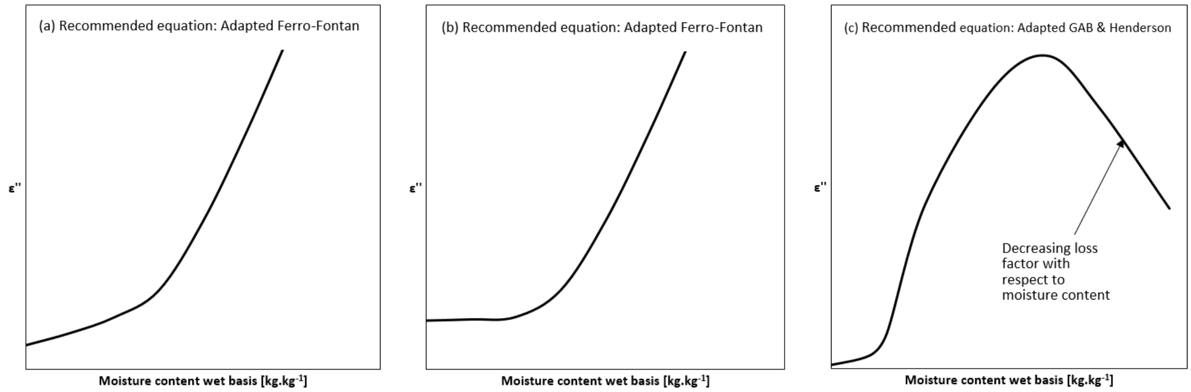

Fig. 4 Recommended application of proposed equations for different dielectric loss profiles

4. Conclusions

Water activity equations have been successfully adapted to accurately describe moisture dependant behaviour of both the loss factor and the dielectric constant. An average best fit MRE of 2.99% was achieved for 30 moisture dependent dielectric response curves (15 loss factor, 15 dielectric constant). These proposed mathematical descriptions for moisture dependant dielectric behaviour represents an important contribution to science, as there is currently no standard method for describing the moisture dependence of dielectrics. These new equations can be used to model microwave drying processes, which are solved at a single frequency. It was found that for an optimum fit, the adapted water activity equation should be selected based on the shape of the dielectric response with respect to moisture content. The adapted Chen equation provided the best average fit for loss factor with respect to moisture content (4.2% MRE), and is recommended for describing a low rise in loss factor, followed by a steep increase in loss factor (a common phenomenon for loss factor moisture dependence). The adapted Ferro-Fontan equation is recommended in instances where the loss factor is initially very flat, followed by a steep rise in loss factor. The adapted GAB and Henderson equations were found to be most effective at describing a negative rate of change of loss factor with respect to moisture content. Currently, microwave and RF applications are optimised through trial and error, which can be costly and ineffective. Being able to model microwave and RF drying processes with the aid of these new equations will enable the optimisation of applicators through modelling, which could reduce costs and improve the probability of success. Algorithms can be used in modelling tools to select moisture dependant equations that describe the correct temperature range of the material. Finally, the equations could potentially be adapted further in future studies to also include temperature dependence.

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Table 1 Sorption isotherm equations adapted to mathematically describe loss factor and dielectric constant with respect to moisture content

Name	Water activity equation	Adapted loss factor equation	Adapted dielectric constant equation
GAB	$a_w = \frac{1}{2}\left(\frac{-2M_{db} + M_{db}C - M_0C + \sqrt{4M_{db}CM_0 + C^2M_{db}^2 - 2M_{db}M_0C^2 + M_0^2C^2}}{M_{db}K(C-1)}\right)$	$\varepsilon'' = \frac{1}{2}\left(\frac{-2M_{wb} + M_{wb}C - M_0C + \sqrt{4M_{wb}CM_0 + C^2M_{wb}^2 - 2M_{wb}M_0C^2 + M_0^2C^2}}{M_{wb}K(C-1)}\right) + \varepsilon''_{0m} - UM_{wb}^S$	$\varepsilon' = \frac{1}{2}\left(\frac{-2M_{wb} + M_{wb}C - M_0C + \sqrt{4M_{wb}CM_0 + C^2M_{wb}^2 - 2M_{wb}M_0C^2 + M_0^2C^2}}{M_{wb}K(C-1)}\right) + \varepsilon'_{0m} - UM_{wb}^S$
Oswin	$a_w = (M_{db}/A)^{1/B}\left(1 + (M_{db}/A)^{1/B}\right)^{-1}$	$\varepsilon'' = C(M_{wb}/A)^{1/B}\left(1 + (M_{wb}/A)^{1/B}\right)^{-1} + \varepsilon''_{0m} - UM_{wb}^S$	$\varepsilon' = C(M_{wb}/A)^{1/B}\left(1 + (M_{wb}/A)^{1/B}\right)^{-1} + \varepsilon'_{0m} - UM_{wb}^S$
Henderson	$a_w = 1 - e^{-ATM_{db}^B}$	$\varepsilon'' = C\left(1 - e^{-ATM_{wb}^B}\right) + \varepsilon''_{0m} - UM_{wb}^S$	$\varepsilon' = C\left(1 - e^{-ATM_{wb}^B}\right) + \varepsilon'_{0m} - UM_{wb}^S$
Chung-Pfost	$a_w = e^{-e^{\frac{M_{db}-a}{b}}}$	$\varepsilon'' = C\left(e^{-e^{\frac{M_{wb}-a}{b}}}\right) + \varepsilon''_{0m} - UM_{wb}^S$	$\varepsilon' = C\left(e^{-e^{\frac{M_{wb}-a}{b}}}\right) + \varepsilon'_{0m} - UM_{wb}^S$
Chen	$a_w = e^{A-Be^{-CM_{db}}}$	$\varepsilon'' = D\left(e^{A-Be^{-CM_{wb}}}\right) + \varepsilon''_{0m} - UM_{wb}^S$	$\varepsilon' = D\left(e^{A-Be^{-CM_{wb}}}\right) + \varepsilon'_{0m} - UM_{wb}^S$
Ferro-Fontan	$a_w = \frac{\gamma}{e^{AM_{db}{}^{r}}}$	$\varepsilon'' = \frac{\gamma}{e^{AM_{dw}{}^{r}}} + \varepsilon''_{0m} - UM_{dw}^S$	$\varepsilon' = \frac{\gamma}{e^{AM_{dw}{}^{r}}} + \varepsilon'_{0m} - UM_{wb}^S$

Table 2 Literature data used to fit proposed moisture dependant dielectric response equations

Food	Source	Dielectric measurement	Type of sorption	Method of dielectric measurement
Potato	(Mudgett et al., 1980)	3GHz at 25°C	Adsorption	Roberts & Von Hippel (Roberts and Von Hippel, 1946) short circuit line technique
Wheat flour	(Kim et al., 1998)	27MHz at 22°C	Desorption	Parallel plate capacitor (Kim et al., 1998)
Chickpea flour	(Guo et al., 2008)	27MHz at 20°C and 90°C, 1.8GHz at 20°C and 90°C	Adsorption	Open-ended coaxial-line probe (Guo et al., 2008)
Yellow dent field corn	(Nelson, 1979)	20MHz at 24°C	Desorption	A Boonton Q-meter, Type 160-A, and the reactance variation method (Nelson, 1979)
Carboxymethyl cellulose	(Nelson et al., 1991)	2.45GHz at 20°C	Adsorption	Roberts & Von Hippel(Roberts and Von Hippel, 1946) short circuit line technique
Hard red winter wheat	(Nelson and Stetson, 1976)	28MHz at 20°C	Mixed	Boonton Type 160-A Q-meter and coaxial sample holder (Nelson et al., 1953)
Hard red winter wheat	(Nelson and Stetson, 1976)	100MHz at 20°C	Mixed	Boonton Type 250-A RX-meter and a coaxial sample holder with open-circuit termination (Jorgensen et al., 1970)
Hard red winter wheat	(Nelson and Stetson, 1976)	1GHz at 20°C	Mixed	Rohde & Schwarz Type LMD slotted line and short-circuited coaxial sample holder used in conjunction with a Type SLRD power signal generator and Type UBK VSWR/null indicator (Nelson, 1973)
Hard red winter wheat	(Nelson and Stetson, 1976)	12.1GHz at 20°C	Mixed	Short-circuited WR-90 waveguide sample holder and a rectangular – waveguide X-band system (Nelson, 1972)
Apples	(Feng et al., 2002)	915MHz and 2.45GHz at 60°C	Desorption	Open-ended coaxial-line probe (Martín-Esparza et al., 2006)
Grapes	(Tulasidas et al., 1995)	2.45GHz at 25°C	Desorption	Open-ended coaxial-line probe (Martín-Esparza et al., 2006)

Table 3 Best fit adapted equations and error for moisture dependant loss factor using experimental data from literature

Food	Best fit adapted model using RSS	Best fit adapted model using MRE	Average fit of 6 equations using MRE [%]	Best fit MRE [%]
Potato 3GHz, 25°C	GAB	GAB	9.73	7.52
Wheat flour 27MHz, 22°C	GAB	GAB	17.8	13.9
Chickpea flour, 27MHz, 20°C	Ferro-Fontan	Ferro-Fontan	2.16	0.0488
Chickpea flour, 27MHz, 90°C	Ferro-Fontan	Ferro-Fontan	0.555	0.0160
Chickpea flour, 1.8GHz, 20°C	Ferro-Fontan	Ferro-Fontan	0.630	0.378
Chickpea flour, 1.8GHz, 90°C	Ferro-Fontan	Ferro-Fontan	0.263	4.81×10^{-4}
Yellow dent field corn, 20MHz, 24°C	Ferro-Fontan	Ferro-Fontan	3.13	1.46
Carboxymethyl cellulose, 2.45GHz, 20°C	Chen	Chen	7.24	2.30
Hard red winter wheat, 28MHz, 20°C	GAB	GAB	5.54	4.73
Hard red winter wheat, 100MHz, 20°C	Ferro-Fontan	Ferro-Fontan	8.26	3.76
Hard red winter wheat, 1GHz, 20°C	Chen	Ferro-Fontan	9.64	6.34
Hard red winter wheat, 12.1GHz, 20°C	GAB	GAB	2.52	1.71
Apples, 915MHz, 60°C	GAB	Chung-Pfost	3.01	2.06
Apples, 2.45GHz, 60°C	Chen	Henderson	4.50	3.16
Grapes, 2.45GHz, 25°C	Owen	Chung-Pfost	0.552	0.00635
			Average best fit MRE =	3.16

Table 4 Best fit equations and error for moisture dependant loss factor of carboxymethyl cellulose and chickpea flour

Model	Parameter	Carboxymethyl cellulose, 2.45GHz, 20°C	Chickpea flour, 27MHz, 20°C	Chickpea flour, 27MHz, 90°C
GAB	M_0	0.254672	0.148977	0.144337
	C	30.83	313.984	347.941
	K	0.346563	0.447778	0.001272
	ε_{0m}''	0.0239977	0.157093	1.621
	U	0	0	0
	S	1	1	1
	MRE [%]	*2.94*	*1.10*	*0.936*
	RSS	*$6.23x10^{-5}$*	*$3.21x10^{-5}$*	*0.0652*
Oswin	A	2.342	0.428069	0.173985
	B	0.367519	0.179429	0.105527
	ε_{0m}''	0.0305853	0.16	4.27
	C	172.46	35.6566	286.905
	U	0	0	0
	S	2.931	1	1
	MRE [%]	*7.51*	*4.72*	*0.976*
	RSS	*$6.43x10^{-4}$*	*$2.81x10^{-3}$*	*0.0262*
Henderson	A	2.34463	48.7627	7570170
	B	3.44696	5.00766	9.07084
	ε_{0m}''	0.0299	0.16	4.27
	C	16.4204	33.496	245.395
	U	0	0	0
	S	1	1	1
	MRE [%]	*24.19*	*4.95*	*1.13*
	RSS	*$9.11x10^{-3}$*	*$1.31x10^{-3}$*	*0.0348*
Chung-Pfost	A	1.08415	0.25209	0.177623
	B	-0.508967	-0.09187	-0.04331
	ε_{0m}''	0.0104272	0.14725	4.27
	C	69.6228	3.25663	396.106
	U	0	0	0
	S	1	1	1
	MRE [%]	*2.30*	*2.03*	*0.137*
	RSS	*$4.51x10^{-5}$*	*$1.01x10^{-4}$*	*$5.37x\ 10^{-4}$*
Chen	A	**-0.2**	-0.2	-0.2
	B	**8.41564**	27.7133	60.403
	ε_{0m}''	**0.0104272**	0.16	4.27
	C	**1.96477**	16.0276	23.0884
	D	**85.0375**	2.0996	483.805
	U	**0**	0	0
	S	**1**	1	1
	MRE [%]	***2.30***	*0.122*	*0.137*
	RSS	***$4.51x10^{-5}$***	*$4.92x10^{-7}$*	*$5.36x10^{-4}$*
Ferro-Fontan	γ	16391.7	**7.16737**	**694.493**
	A	7.86524	**0.23706**	**0.019329**
	r	-0.213432	**-1.47887**	**-2.54963**
	ε_{0m}''	0.0299639	**0.16**	**4.27**
	U	0	**0**	**0**
	S	1	**1**	**1**
	MRE [%]	*4.19*	***0.0488***	***0.0160***
	RSS	*$3.21x10^{-3}$*	***$8.42x10^{-8}$***	***$9.23x10^{-6}$***

Table 5 Best fit equations and error for moisture dependant loss factor of chickpea flour, yellow corn, and potato

Model	Param-eter	Chickpea flour, 1.8GHz, 20°C	Chickpea flour, 1.8GHz, 90°C	Yellow corn, 20MHz, 24°C	Potato 3GHz, 25°C
GAB	M_0	0.15495	0.115617	0.2458	**0.239536**
	C	154.075	480.983	75.5168	**79.2961**
	K	0.814818	0.0501527	0.1287	**0.0220823**
	ε_{0m}''	0.187	1.4576	0.3176	**0.06**
	U	0	0	0	**23.6205**
	S	1	1	1	**2.53325**
	MRE [%]	*0.989*	*0.385*	*4.87*	***7.52***
	RSS	$3.26x10^{-5}$	$6.15x10^{-4}$	*0.00784*	***1.98***
Oswin	A	0.236836	0.15325	0.319799	0.3185
	B	0.186796	0.11282	0.182564	0.1911
	ε_{0m}''	0.19	1.54	0.391672	0.1
	C	0.97446	9.41576	3.86791	22.1806
	U	0	0	0	11.2911
	S	1	1	1	5.1281
	MRE [%]	*0.482*	*0.461*	*3.55*	*7.65*
	RSS	$8.30x10^{-6}$	$7.05x10^{-4}$	$3.72x10^{-3}$	*2.89*
Henderson	A	3387.83	1419050	322.814	228.852
	B	5.31254	7.71968	4.99957	4.902
	ε_{0m}''	0.1893	1.54	0.383664	0.1
	C	0.58593	8.85282	2.95338	20.372
	U	0	0	0	9.525
	S	1	1	1	7.203
	MRE [%]	*0.548*	*0.691*	*4.14*	*7.73*
	RSS	$7.71x10^{-6}$	$1.53x10^{-3}$	$4.96x10^{-3}$	*4.06*
Chung-Pfost	A	0.25841	0.143628	0.3022	0.289
	B	-0.09557	-0.029444	-0.09684	-0.0951
	ε_{0m}''	0.18943	1.54	0.4079	0.1
	C	1.7345	9.86506	4.39396	22.715
	U	0	0	0	11.8636
	S	1	1	1	4.5917
	MRE [%]	*0.889*	*0.0208*	*2.37*	*11.8*
	RSS	$4.89x10^{-5}$	$1.55x10^{-6}$	$1.80x10^{-3}$	*2.83*
Chen	A	-0.2	-0.2	-0.2	-0.2
	B	14.8124	131.372	22.6635	20.9033
	ε_{0m}''	0.19	1.54	0.4079	0.1
	C	10.2752	33.963	10.3267	10.5181
	D	2.27264	12.0492	5.3668	27.7441
	U	0	0	0	11.8636
	S	1	1	1	4.5917
	MRE [%]	*0.497*	*0.0207*	*2.36*	*9.53*
	RSS	$8.02x10^{-6}$	$1.55x10^{-6}$	$1.80x10^{-3}$	*3.04*
Ferro-Fontan	γ	**328.446**	**11.1322**	**8.53813**	31.6472
	A	**2.83126**	**0.0003407**	**0.18407**	0.0755
	r	**-0.569336**	**-4.16019**	**-1.84519**	-2.2729
	ε_{0m}''	**0.19**	**1.54**	**0.41618**	0.1
	U	**0**	**0**	**0**	18.5434
	S	**1**	**1**	**1**	2.9831
	MRE [%]	***0.378***	$\mathbf{4.81x10^{-4}}$	***1.46***	*14.2*
	RSS	$\mathbf{4.69x10^{-6}}$	$\mathbf{6.69x10^{-10}}$	$\mathbf{6.56x10^{-4}}$	3.10^{3}

Table 6 Best fit equations and error for moisture dependant loss factor of hard red winter wheat

Model	Param-eter	Winter wheat, 28MHz, 24°C	Winter wheat, 100MHz, 24°C	Winter wheat, 1GHz, 24°C	Winter wheat, 12.1GHz, 24°C
GAB	M_0	**0.344873**	0.349546	0.403125	**0.129941**
	C	**203.973**	354.812	636.836	**14.8015**
	K	**0.0151858**	0.00852868	0.00468425	**0.851807**
	ε_{0m}''	**0.296256**	0.157668	0.112751	**0.0604961**
	U	**0**	0	0	**0**
	S	**1**	1	1	**1**
	MRE [%]	***4.73***	*14.2*	*15.9*	***1.71***
	RSS	***0.0119***	*0.0949*	*0.0445*	***6.49×10^{-4}***
Oswin	A	5.94481	128.042	200	0.185644
	B	0.39494	1.14929	1.2	0.356381
	ε_{0m}''	0.361881	0.0290887	0.05	0.081624
	C	1733.86	150.559	114	0.829525
	U	0	0	0	0
	S	1	1	1	1
	MRE [%]	*5.26*	*7.47*	*11.2*	*2.58*
	RSS	*0.0170*	*0.0164*	*0.0175*	*7.94×10^{-4}*
Henderson	A	2.1199	0.1683	0.2221	76.5329
	B	2.5511	1.3272	1.3301	2.53812
	ε_{0m}''	0.3025	0.13	0.100043	0.0786965
	C	11.3655	22.3422	12.2164	0.640597
	U	0	0	0	0
	S	1	1	1	1
	MRE [%]	*6.54*	*7.35*	*11.8*	*2.18*
	RSS	*0.0235*	*0.0213*	*0.0230*	*6.69×10^{-4}*
Chung-Pfost	A	1.482	2.036	0.101262	0.143608
	B	-0.83477	-1.063	-0.037481	-0.078064
	ε_{0m}''	0.1283	-0.012	0.118837	0.074957
	C	58.2089	148.312	0.332885	0.755439
	U	0	0	0	0
	S	1	1	1	1
	MRE [%]	*5.05*	*9.09*	*6.34*	*2.35*
	RSS	*0.0264*	*0.0211*	*5.66×10^{-3}*	*7.57×10^{-4}*
Chen	A	-0.2	-0.2	**-0.2**	-0.2
	B	4.1705	2.7802	**14.9054**	6.2941
	ε_{0m}''	0.1213	-0.4613	**0.1188**	0.075
	C	1.5069	0.8481	**26.6804**	12.8099
	D	14.4146	12.5504	**0.4066**	0.9227
	U	0	0	**0**	0
	S	1	1	**1**	1
	MRE [%]	*6.46*	*7.63*	***6.34***	*2.35*
	RSS	*0.0517*	*0.0110*	***5.66×10^{-3}***	*7.57×10^{-4}*
Ferro-Fontan	γ	756.552	**47.3801**	**0.368**	1.74091
	A	5.23	**3.71787**	**0.00295**	0.28366
	r	-0.23	**-0.128881**	**-2.58964**	-0.97448
	ε_{0m}''	0.31	**0.0326455**	**0.12387**	0.089
	U	0	**0**	**0**	0
	S	1	**1**	**1**	1
	MRE [%]	*5.23*	***3.76***	***6.34***	*3.94*
	RSS	*0.0219*	***5.25×10^{-3}***	*5.80×10^{-3}*	*1.29×10^{-3}*

Table 7 Best fit equations and error for moisture dependant loss factor of wheat flour, apples, and grapes

Model	Param-eter	Wheat flour 27MHz, 22°C	Apples, 915MHz, 60°C	Apples, 2.45GHz, 60°C	Grapes, 2.45GHz, 25°C
GAB	M_0	**0.316431**	**0.164872**	0.1197	0.149865
	C	**86.5181**	**11.9272**	50.0798	114.694
	K	**0.00486168**	**0.0881887**	0.1151	0.0393911
	ε_{0m}''	**0.4**	**0.475638**	0.4929	0.01
	U	**144.25**	**0**	0	7.83352
	S	**3.61254**	**1**	1	4.02769
	MRE [%]	***13.9***	*2.09*	*5.97*	*1.19*
	RSS	***284***	***0.0170***	*0.239*	*0.0143*
Oswin	A	0.480112	0.26127	0.20605	**0.2744**
	B	0.24278	0.45394	0.30369	**0.2543**
	ε_{0m}''	0.6	0.5	0.54151	**0.5**
	C	164.243	9.64016	7.04807	**18.8393**
	U	156.033	0	0	**3.7319**
	S	2.63174	1	1	**3.8989**
	MRE [%]	*18.3*	*3.69*	*3.90*	*0.0134*
	RSS	*294*	*0.0316*	*0.0347*	$\boldsymbol{1.52x10^{-6}}$
Henderson	A	18.7981	8.82226	**28.9077**	27.9119
	B	3.91258	1.79028	**2.352**	2.8882
	ε_{0m}''	0.6	0.46179	**0.3962**	0.1
	C	94.2381	8.64366	**6.9376**	18.2055
	U	95.864	0	**0**	1.8519
	S	4.54715	1	**1**	3.7274
	MRE [%]	*17.1*	*3.10*	***3.16***	$6.43x10^{-3}$
	RSS	*315*	*0.0577*	*0.0772*	$3.28x10^{-6}$
Chung-Pfost	A	0.410623	**0.18923**	0.17253	**0.229546**
	B	-0.151555	**-0.1362**	-0.08553	**-0.098623**
	ε_{0m}''	0.6	**0.27428**	0.49017	**0.1**
	C	140.911	**8.98557**	6.93145	**18.822**
	U	138.744	**0**	0	**3.0279**
	S	3.02858	**1**	1	**3.57035**
	MRE [%]	*18.5*	***2.06***	*3.25*	$\boldsymbol{6.35x10^{-3}}$
	RSS	*290*	*0.0294*	*0.0346*	$4.25x10^{-6}$
Chen	A	-0.429978	-0.2	**-0.2**	-0.2
	B	18.0783	4.0121	**7.5166**	9.9624
	ε_{0m}''	0.6	0.2743	**0.4902**	0.1
	C	7.29881	7.3419	**11.6913**	9.9718
	D	193.59	10.975	**8.4661**	23.0762
	U	122.08	0	**0**	2.9022
	S	3.16938	1	**1**	3.0963
	MRE [%]	*19.0*	*2.06*	*3.25*	*0.527*
	RSS	*305*	*0.0294*	***0.0346***	*0.0174*
Ferro-Fontan	γ	209.853	10.7284	7.38927	26.4428
	A	0.253044	0.1566	0.03107	0.0968
	r	-1.89453	-1.2679	-1.9858	-1.7111
	ε_{0m}''	0.6	0.8371	0.62957	0.1
	U	166.929	0	0	9.5438
	S	3.19123	1	1	2.2585
	MRE [%]	*20.2*	*5.05*	*7.49*	*1.56*
	RSS	*322*	*0.0669*	*0.145*	*0.109*

Table 8 Best fit equations and error for moisture dependant dielectric constant of carboxymethyl cellulose and chickpea flour

Model	Param-eter	Carboxymethyl cellulose, 2.45GHz, 20°C	Chickpea flour, 27MHz, 20°C	Chickpea flour, 27MHz, 90°C
GAB	M_0	**0.237549**	**0.1258**	0.109691
	C	**30.6258**	**6988.2**	8.55×10^{15}
	K	**0.160305**	**0.258574**	0.007734
	ε_{0m}''	**1.88**	**2.96**	11
	U	**0**	**0**	0
	S	**1**	**1**	1
	MRE [%]	***0.867***	***0.296***	*2.29*
	RSS	***0.00350***	***9.28x10^{-4}***	*2.97*
Ferro-Fontan	γ	52900	2.03727	**68.463**
	A	7.87	0.000304	**3.91x10^{-5}**
	r	-0.23	-4.35932	**-5.14112**
	ε_{0m}''	1.885	2.96	**11.0125**
	U	0	0	**0**
	S	1	1	**1**
	MRE [%]	*0.894*	*0.589*	***0.449***
	RSS	*0.00547*	*0.00250*	***0.0356***

Table 9 Best fit equations and error for moisture dependant dielectric constant of chickpea flour, yellow corn, and potato

Model	Param-eter	Chickpea flour, 1.8GHz, 20°C	Chickpea flour, 1.8GHz, 90°C	Yellow corn, 20MHz, 24°C	Potato 3GHz, 25°C
GAB	M_0	**0.126279**	**0.109877**	0.181295	**0.354477**
	C	**8.57821x10^{16}**	**3974.59**	12.08	**17**
	K	**0.573614**	**0.026918**	0.137047	**0.00948917**
	ε_{0m}''	**2.43**	**6.18227**	2.9	**2.9**
	U	**0**	**0**	0	**0**
	S	**1**	**1**	1	**1**
	MRE [%]	***2.28x10^{-5}***	***0.388***	*0.846*	***7.82***
	RSS	***3.68x10^{-12}***	***0.0106***	*0.0123*	*42.7*
Ferro-Fontan	γ	0.754667	21.1925	**13.7021**	**148.531**
	A	5.27023×10^{-7}	0.000176	**0.577934**	**0.740834**
	r	-7.68726	-4.42187	**-0.75582**	**-0.941881**
	ε_{0m}''	2.43	6.095	**2.9**	**4.1**
	U	0	0	**0**	**0**
	S	1	1	**1**	**1**
	MRE [%]	*0.0254*	*0.584*	***0.351***	*8.90*
	RSS	*5.30x10^{-6}*	*0.0132*	***0.00283***	***42.1***

Table 10 Best fit equations and error for moisture dependant dielectric constant of hard red winter wheat

Model	Param-eter	Winter wheat, 28MHz, 24°C	Winter wheat, 100MHz, 24°C	Winter wheat, 1GHz, 24°C	Winter wheat, 12.1GHz, 24°C
GAB	M_0	**0.0961587**	**0.095264**	0.199258	**0.071629**
	C	**12.6635**	**19.1273**	2.89676	**19.1556**
	K	**0.228871**	**0.248974**	0.289928	**1.01819**
	ε_{0m}''	**2.54535**	**2.40137**	2.01	**2.15512**
	U	**0**	**0**	0	**0**
	S	**1**	**1**	1	**1**
	MRE [%]	***1.15***	***1.30***	*2.47*	***0.726***
	RSS	***0.0688***	***0.0567***	*0.100*	***0.00825***
Ferro-Fontan	γ	4.354	3.43102	**5.34534**	0.78988
	A	0.0901699	0.03877	**0.586264**	0.015985
	r	-1.24301	-1.60761	**-0.61455**	-1.78049
	ε_{0m}''	2.70113	2.53346	**2.16314**	2.19741
	U	0	0	**0**	0
	S	1	1	**1**	1
	MRE [%]	*1.59*	*1.69*	***2.09***	*0.781*
	RSS	*0.0886*	*0.0745*	***0.0877***	*0.00884*

Table 11 Best fit equations and error for moisture dependant dielectric constant of wheat flour, apples, and grapes

Model	Param-eter	Wheat flour 27MHz, 22°C	Apples, 915MHz, 60°C	Apples, 2.45GHz, 60°C	Grapes, 2.45GHz, 25°C
GAB	M_0	**0.339663**	0.193923	0.22174	**0.382367**
	C	**5.89623**	11.9273	12.2115	**12.6314**
	K	**0.00899103**	0.024558	0.024997	**0.00817**
	ε_{0m}''	**3.516**	2.647	2.60398	**2.43**
	U	**0**	0	0	**0**
	S	**1**	1	1	**1**
	MRE [%]	***0.844***	*4.01*	*4.90*	***0.857***
	RSS	***1.40***	*1.71*	*2.04*	***0.709***
Ferro-Fontan	γ	188.162	**42.3973**	**45.4747**	300
	A	0.88041	**0.2555**	**0.355964**	1.307
	r	-0.62442	**-1.1191**	**-1.03357**	-0.632
	ε_{0m}''	3.516	**3.73717**	**3.5612**	3.6
	U	0	**0**	**0**	0
	S	1	**1**	**1**	1
	MRE [%]	*3.97*	***3.98***	***3.41***	*3.94*
	RSS	*16.9*	***1.21***	***1.16***	*7.65*

Table 12 Performance of adapted water activity equations at curve fitting to 15 moisture dependant loss factor measurements

Adapted water activity equation for loss factor	Average MRE of 15 moisture dependent loss factor fits	Number of MRE best fits
GAB	5.2	4
Oswin	5.2	0
Henderson	6.3	1
Chung-Pfost	4.4	2
Chen	4.2	1
Ferro-Fontan	4.9	7