

This is the author-created version of the following work:

Shishir, Md Safiqur Rahaman, Jacob, Mohan, Leong, Kenneth, Cheng, Long, Cullen, Brendan, and Brodie, Graham (2021) *Measurement and modelling of dielectric properties of different animal feed resources as a function of feed type and moisture content*. Journal of Microwave Power and Electromagnetic Energy, 55 (4) pp. 273-286.

Access to this file is available from:

<https://researchonline.jcu.edu.au/70545/>

© 2021 International Microwave Power Institute.

Please refer to the original source for the final version of this work:

<https://doi.org/10.1080/08327823.2021.1993048>

Measurement and modelling of dielectric properties of different animal feed resources as a function of feed type and moisture content

Md Safiqur Rahaman Shishir^{a, d}, Mohan Jacob^c, Kenneth Leong^c, Long Cheng^a, Brendan Cullen^b, Graham Brodie^{a, c, *}

^a *The University of Melbourne, Melbourne, Dookie Campus, VIC 3647, Australia;*

^b *The University of Melbourne, Parkville, VIC 3010, Australia;*

^c *College of Science and Engineering, James Cook University, Townsville, QLD 4810 Australia*

^d *Department of Animal Nutrition, Bangladesh Agricultural University, MYM 2202, Bangladesh*

*Corresponding Author: Graham Brodie

Email: grahamb@unimelb.edu.au

The University of Melbourne, Melbourne, Dookie Campus, VIC 3647, Australia

Biographical notes

Md Safiqur Rahaman Shishir is currently a Ph.D. student at the University of Melbourne, Faculty of Veterinary and Agricultural Sciences. He received his bachelor's degree in Animal Husbandry from Bangladesh Agricultural University (BAU), Bangladesh, and a master's degree in Animal Nutrition from the Department of Animal Nutrition, BAU. He is interested in the application of novel processing techniques on animal feed for improving quality. ORCID ID: <https://orcid.org/0000-0002-4769-2820>

Dr. Mohan V. Jacob is a Professor in Electrical Engineering and Associate Dean Research Education at James Cook University. He obtained his Ph.D. from University of Delhi in 1999. He is actively involved in non-destructive characterization of various materials at microwave frequencies and cryogenic temperatures. He is also involved in developing sustainable, natural resource-based environmentally friendly biomaterials and electronic and biomedical devices. He developed graphene from non-conventional sustainable sources using plasma-enhanced chemical vapor deposition. He published over 150 peer-reviewed journal papers and conference papers. ORCID ID <https://orcid.org/0000-0002-2598-7193>

Kenneth Leong received the B.Eng. (with honors) and a Ph.D. degree in electrical engineering from the James Cook University, Townsville, Qld., Australia, in 1994 and 2000, respectively. He is currently in the lecturer position in the School of Engineering, James Cook University, where he is involved with microwave measurements on materials including high- T_c thin-film superconductors and dielectrics for applications in wireless communications. His novel development is known as the TMQF, which is currently being utilized at the James Cook University for accurate measurements of the surface resistance parameter of high- T_c thin-film superconductor. ORCID ID <https://orcid.org/0000-0003-3707-8998>

Dr. Long Cheng graduated from Lincoln University (New Zealand's specialist land-based university), New Zealand, in 2008, with a Bachelor of Agricultural Science with Honours. In 2009, Dr. Cheng commenced his Ph.D., investigating the use of nitrogen isotopic fractionation as a biomarker to indicate nitrogen use efficiency of ruminants, graduating in 2013 from Lincoln University, New Zealand. Dr. Cheng's research interest includes energy and nitrogen metabolism, Precision agriculture, Nitrogen use efficiency in ruminant animals. ORCID ID: <http://orcid.org/0000-0002-8483-0495>

Dr. Brendan Cullen is a Senior lecturer in Sustainable Agriculture (Pasture Systems) in the Faculty of Veterinary & Agricultural Sciences at the University of Melbourne. Over the last 15 years, Brendan has worked on a series of research projects with the dairy and red meat industries to understand the impacts of projected climate changes on livestock production businesses across Australia. The research aims to identify industry pathways that are adapted to a variable and changing climate, using farms systems modelling approaches. Brendan has published more than 40 peer-reviewed scientific papers and currently supervise 3 Ph.D. students working in this field. He also teaches into the Bachelor and Masters coursework programs on pasture and livestock production, livestock production systems, dairy systems, and climate change adaptation. ORCID ID: <https://orcid.org/0000-0003-2327-0946>

Dr. Graham Brodie is an Associate Professor in the Faculty of Veterinary and Agricultural Sciences. He earned his electrical engineering degree from James Cook University and worked in the electrical power industry before turning his hand to academia. Dr. Brodie's research interests include microwave heating of bio-materials; using microwaves for sensing and communication in agriculture and forestry; improving water use efficiency in agriculture; producing renewable energy on farms; on-farm animal waste management; and applications of Geographic Information System (GIS) and Remote Sensing technologies in agriculture and archaeology. ORCID ID: <https://orcid.org/0000-0003-2085-4671>

66 **Acknowledgment**

67 The authors want to acknowledge Dr. Ravneet Kaur, Laboratory manager, Dookie Analytical
68 laboratory, for assisting with the laboratory work.

69

70

71

72

73

74

75

76

77

78

79

80

81

82

83

84

85

86

87

88 **Measurement and modelling of dielectric properties of different**
89 **animal feed resources as a function of feed type and moisture content**

90

Abstract

Dielectric properties of any particular material will determine the level of microwave (MW) heating. Therefore, measurement of the dielectric properties of MW treatment subject materials are necessary. This study investigated the dielectric properties of six roughages and three concentrate animal feeds across the microwave frequency range of 1×10^9 to 5×10^9 Hz. Six treatment groups, named control (at equilibrium moisture constant), oven dried (0 % moisture), 25% moisture added, 50% moisture added, 75% moisture added, and 100% moisture added groups were prepared for the study. Three separate replications and five observations for each replication were used to assess the dielectric properties of these materials. The results showed that for increasing moisture content, from oven-dried, though the control status, to 100% added moisture, both the dielectric constant (real part) and the dielectric loss factor (imaginary part) increased for both the roughages and concentrates. However, the responses were not linear. The oven-dried plant samples' dielectric properties were very low compared with those of the higher moisture content samples. Thus, the sample's moisture content was the dominant contributor to the feed samples' dielectric behavior. Among all the feed samples, faba bean and wheat grain showed the highest response to added moisture. Mathematical models were developed to explain the dielectric properties of feeds as a function of frequency and moisture content. The goodness of fit (r^2) for these models' real part varied between 0.85-0.99 for roughage and 0.98-0.99 for concentrate feed type. On the other hand, the goodness of fit for the imaginary part varied between 0.59-0.78 for roughage, and 0.81-0.93 for concentrate feeds.

Keywords: forage; grain; moisture; dielectric, modelling

Introduction

Microwave (MW) technology is becoming more popular for uses in the human food and animal feed processing industries (Chandrasekaran et al. 2013) due to its quick and energy-efficient processing ability. It proved to be effective in improving human food (Puligundla et al. 2013) and animal feed (Brodie et al. 2019) nutritive value. Several uses of MW heat energy have been observed for the feed processing industry, such as

drying, moisture measurement, removal of antinutritional factors, and improving quality (Park et al. 1983; Higgins and Spooner 1986; Mahyuddin et al. 1988; Trabelsi et al. 2013). It is evident that the nutritive value of roughage and concentrate feed, for better animal production, can be improved using MW heat treatment (Dong et al. 2005; Sadeghi et al. 2005; Sadeghi and Shawrang 2006, 2008; Brodie et al. 2012). However, it is necessary to understand the feed material's behavior when subjected to MW energy (Nelson and Stetson 1975). The dielectric properties of the material determine interactions between materials and electromagnetic waves. Therefore, the dielectric properties of roughage and concentrate feeds play a significant role in applying MW energy when it is being considered for processing. This knowledge of the dielectric properties is required to optimize MW processing.

Many materials, which are regularly processed with Radio Frequency (RF), MW, and millimeter-wave (mm-Wave) energy, contain bound and free water. The water in materials, such as forage hay and grains, which is below saturation, is predominantly bound water (Brusewitz et al. 1993). This is water, which is hygroscopically fixed to the surface of the forage or grain's underlying cellular structure. Unlike free water, the dipole molecules in bound water are less free to respond to oscillating electromagnetic fields; therefore, its characteristic response frequency is much lower than that of free water (Esch et al. 1999).

Debye (1929) developed the following basic model for the dielectric behavior of materials with polar molecules:

$$\varepsilon_{ef} = \varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + j\frac{f}{f_o}} + j\frac{\sigma}{2\pi\varepsilon_0 f} \quad (1)$$

Where ε_{ef} is the complex dielectric constant at any frequency (f), ε_{∞} is the complex dielectric constant at very high frequencies, ε_s is the dielectric constant at very

low frequencies, f_o is the fundamental response frequency of the dipolar molecules, σ is the electrical conductivity of the material, ϵ_o is the dielectric properties of free space, and $j = \sqrt{-1}$, which is the complex operator.

Debye's Equation applies to pure dipolar materials, with a single fundamental response frequency. Most real materials have a dispersed response to the electromagnetic fields, so Cole and Cole (1941) developed a modified variant of the Debye equation to account for these dispersed responses:

$$\epsilon_{ef} = \epsilon_{\infty} + \frac{\epsilon_s - \epsilon_{\infty}}{1 + (j \frac{f}{f_o})^{(1-\alpha)}} + j \frac{\sigma}{2\pi \epsilon_o f} \quad (2)$$

Where α represents the level of dispersion in the response and can be determined by plotting the real and imaginary components of ϵ_{ef} in the complex plain.

Previous studies about the dielectric properties of some plant materials and grains, with a diverse range of frequencies up to 15 GHz, already exist (Nelson and Stetson 1975; Nelson 1981); however, there seems to be no specific data available on the dielectric properties of roughage (forage hay, straw) and concentrate feeds related to different moisture content at different frequencies. Therefore, this study was conducted with the following objectives: to (1) measure the dielectric properties of roughage and concentrate feeds over the range of 1×10^9 Hz to 5×10^9 Hz, (2) identify the relationship between feed type, and moisture content, frequency, and dielectric properties, and (3) determine the penetration depth within the selected frequency range to estimate the heat distribution.

Materials and methods

The study was conducted at the Douglas Campus, James Cook University, Townsville, Queensland, Australia.

Feed sample collection

To investigate the dielectric properties of different feed samples, nine types of feed, consisting of six roughages and three concentrates, were used in this study. The roughage feeds were lucerne hay(*Medicago sativa*), canola hay(*Brassica napus*), pasture hay (perennial ryegrass; *Lolium perenne*. L + white clover; *Trifolium repens*), oaten hay (*Avena sativa*), wheaten hay (*Triticum aestivum*), and rice straw. The concentrate feed samples were faba bean grain (*Vicia faba*), wheat grain (*Triticum aestivum*), and maize grain (*Zea mays*). Lucerne hay, pasture hay, and maize grain were purchased from a farm supply store in Shepperton, northern Victoria, Australia. Oaten hay was collected from a sheep farm near Dookie Campus, northern Victoria, Australia. Wheaten hay, canola hay, wheat grain, and faba bean grain were collected from the Dookie Campus sheep farm at The University of Melbourne, northern Victoria, Australia. Rice straw was collected from a local contact close to Shepperton, northern Victoria, Australia.

Feed sample preparation

Initially, moisture and DM content of each type of feed were measured according to Association of Official Agricultural Chemists (AOAC) 925.10 (AOAC 1990). To observe the change in different feed samples' dielectric properties, samples were ground with a coffee grinder prior to passing the material through a 2 mm sieve. One equilibrium moisture content (EMC) control group and five-levels of different moisture were added to each feed type to achieve five moisture added group sample at 0% (oven dried), 25%, 50%, 75%, and 100% moisture, based on their DM weight. The selected amount of deionized water for each treatment was sprayed onto the feed sample, which was kept in a polyethylene zip lock bag and mixed thoroughly at least twice per day while keeping them refrigerated at 4°C to ensure that the moisture was distributed

uniformly. Samples are stored in the refrigerator for three days before the experiment was conducted.

Experimental design

The experimental design of the current study is illustrated in Table 1

Table 1: Illustration of experimental design to determine dielectric properties of animal feed

Feed type	Moisture content	No of Replication	No of observation
Roughage			
Lucerne, Canola, Pasture. Oat, wheat hay, and rice straw	Control	3	5
	0% (Oven dried)	3	5
	25%	3	5
	50%	3	5
	75%	3	5
	100%	3	5
Concentrate			
Faba bean, wheat, and maize grain	Control	3	5
	0% (Oven dried)	3	5
	25%	3	5
	50%	3	5
	75%	3	5
	100%	3	5

Dielectric properties measurement

For measurement of complex permittivity (real part, ϵ' , and imaginary part, ϵ'') of the feed samples the procedure of (Taheri et al. 2018) was followed. An open-ended coaxial probe kit (Agilent 85070E Dielectric Probe kit 200 MHz to 50 GHz, Performance Probe 85070-60010) with a network analyzer (E8364B PNA network analyzer) was used to measure the dielectric properties in the frequency range of 1×10^9 Hz to 5×10^9 Hz (Figure 1). The network analyzer was connected to a computer with Agilent software. To avoid any errors, the connecting cable and the probe remained fixed during

measurement. Calibration was conducted within open-air, water, and an aluminum sheet before starting the measurement. To confirm the calibration, the dielectric properties of water, which are well known at room temperature, were measured. After making these measurements match the correct water curves, the measurements on feed samples were carried out.

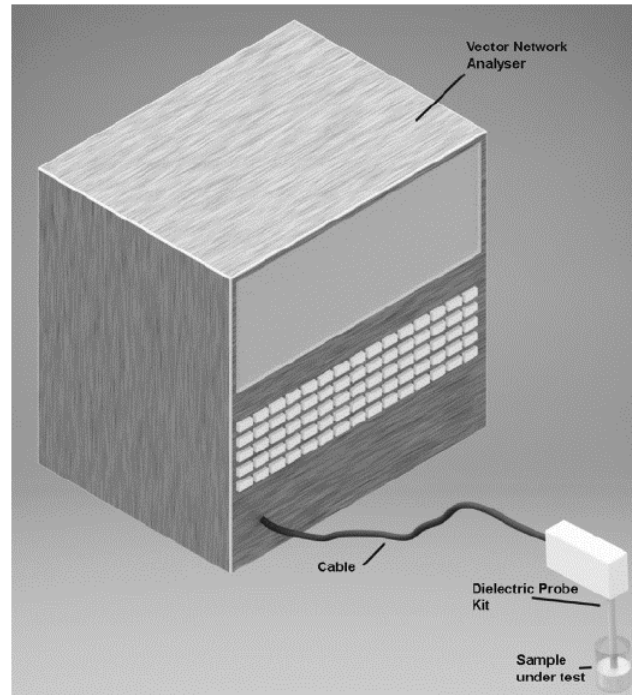


Figure 1. Schematic of vector network analyzer (E8364B PNA) with open-ended coaxial probe kit and sample under test. (adopted from Kabir et al. (2020))

Three replications of each treatment sample were measured for dielectric properties. For each replication, five data observations were collected from the vector network analyzer, after the dielectric probe was removed and reinserted into a different part of the sample. The mean values were considered for further statistical analysis. The sample was placed in a Teflon container (4.5 cm length x 1 cm diameter) to measure the dielectric properties via the probe. Feed samples were placed in the container in a manner to create a plain surface, assuming that there is no other influence during measurement. During the measurement, room temperature (25 ± 2 °C) was maintained.

For the measurement of the feed samples' dielectric properties, with an open-ended coaxial probe, the sample must have a flat surface and be kept in contact with the probe. When the solid sample comes into contact with the probe, a signal will be reflected and measured as a flat surface. Finally, the measurement will be related to the relative permittivity.

Penetration depth and wavelength

The depth, where the microwave power drops to 1/e (e = 2.718) or 36.8% of its primary value in a material, is known as the "penetration depth." (Metaxas and Meredith 1983)

$$dp = \frac{c}{2\pi f \sqrt{2\epsilon'}} \quad (3)$$

The penetration depth is calculated from the dielectric properties of that material, using Equation (3), where c is the speed of light in free space (3×10^8 m/s), and f is the frequency (Hz). The penetration depth is inversely proportional to the frequency. The higher the frequency, the lower the penetration depth into the material, and as a result, surface heating will increase.

$$\lambda_m = \frac{c\sqrt{2}}{f\sqrt{\epsilon'^2 + \epsilon''^2 + \epsilon'}} \quad (4)$$

The MW or RF field wavelength inside the material is inversely related to the frequency and modified by the material's dielectric properties. Therefore, the wavelength in the material can be calculated by using the dielectric properties in Equation (4). Prediction of MW heat treatment is possible when the penetration depth, wavelength, and geometrical structure of the applicator and load material are known (Brodie GI 2008; Bhattacharya and Basak 2017).

Dielectric Model for Forage Materials as a Function of Frequency and Moisture Content

From their study of the dielectric properties of vegetation, Ulaby FT and El-Rayes (1987) determined that the dispersion constant α in Equation (2), for bound water, was 0.5. Therefore, assuming that (1) the bound water is the most dominant factor in the dielectric constant of unsaturated forage or grain, (2) there is little electrical conductivity in the samples, and (3) that the dry forage has a small residual dielectric behavior, the dielectric properties of forages and grains can be described by:

$$\varepsilon_{ef} = \varepsilon_{dr} + j\varepsilon_{di} + F(m) \left[\varepsilon_{\infty} + \frac{\varepsilon_s - \varepsilon_{\infty}}{1 + \sqrt{\left(j\frac{f}{f_o}\right)}} \right] + j \frac{\sigma}{2\pi\varepsilon_o f} \quad (5)$$

Where ε_{dr} is the real part of the residual dielectric behavior of the dry material, ε_{di} is the imaginary part of the residual dielectric behavior of the dry material, and $F(m)$ is some function of the moisture content that is to be determined from the experimental data.

The portion of Equation (5), described by $\frac{\varepsilon_s - \varepsilon_{\infty}}{1 + \sqrt{\left(j\frac{f}{f_o}\right)}}$, can be partially resolved by multiplying the top and bottom of the fraction by $1 - \sqrt{\left(j\frac{f}{f_o}\right)}$ to become:

$$\frac{(\varepsilon_s - \varepsilon_{\infty}) \left[1 - \sqrt{\left(j\frac{f}{f_o}\right)} \right]}{1 - j\frac{f}{f_o}} \quad (6)$$

This can be further resolved by multiplying the top and bottom of the fraction by $1 + j\frac{f}{f_o}$ to become:

$$\frac{(\varepsilon_s - \varepsilon_\infty) \left[1 - \sqrt{j \frac{f}{f_o}} \right] \left[1 + j \frac{f}{f_o} \right]}{1 + \left(\frac{f}{f_o} \right)^2} \quad (7)$$

Knowing that the $\sqrt{j} = \frac{1}{\sqrt{2}} + j \frac{1}{\sqrt{2}}$, the first square bracket of the numerator now needs to be expanded to become:

$$\frac{(\varepsilon_s - \varepsilon_\infty) \left[1 - \frac{1}{\sqrt{2}} \sqrt{\left(\frac{f}{f_o} \right)} - j \frac{1}{\sqrt{2}} \sqrt{\left(\frac{f}{f_o} \right)} + j \frac{f}{f_o} - j \frac{1}{\sqrt{2}} \left(\frac{f}{f_o} \right) \sqrt{\left(\frac{f}{f_o} \right)} + \frac{1}{\sqrt{2}} \left(\frac{f}{f_o} \right) \sqrt{\left(\frac{f}{f_o} \right)} \right]}{1 + \left(\frac{f}{f_o} \right)^2} \quad (8)$$

This can be resolved into its real and imaginary part so that all the dielectric properties of unsaturated forage or grain can be described by:

$$\varepsilon'_{ef} = \varepsilon_{dr} + F(m) \left[\varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty) \left[1 - \frac{1}{\sqrt{2}} \sqrt{\left(\frac{f}{f_o} \right)} + \frac{1}{\sqrt{2}} \left(\frac{f}{f_o} \right) \sqrt{\left(\frac{f}{f_o} \right)} \right]}{1 + \left(\frac{f}{f_o} \right)^2} \right] \quad (9)$$

And

$$\varepsilon''_{ef} = \varepsilon_{di} + F(m) \left[\frac{(\varepsilon_s - \varepsilon_\infty) \left[\frac{f}{f_o} - \frac{1}{\sqrt{2}} \sqrt{\left(\frac{f}{f_o} \right)} - \frac{1}{\sqrt{2}} \left(\frac{f}{f_o} \right) \sqrt{\left(\frac{f}{f_o} \right)} \right]}{1 + \left(\frac{f}{f_o} \right)^2} \right] + \frac{\sigma}{2\pi \varepsilon_o f} \quad (10)$$

Where $\varepsilon_{ef} = \varepsilon'_{ef} + j\varepsilon''_{ef}$

A second-order polynomial was used to account for changes in moisture:

$$F(m) = 1 + b \cdot m + c \cdot m^2 \quad (11)$$

280 *Statistical and other software analysis*

281 Dielectric data were analyzed and displayed with the help of MATLAB software
 282 (MathWorks, Inc., USA). Equations (9) to equations (11) were used in MatLab's Curve

Fitting Tool as the basis for developing a semi-empirical model for the dielectric properties of the forages and concentrates.

Results and discussion

Figure 2 shows the results of applying the model equations to the real and imaginary parts of the measured dielectric properties for roughage and concentrate feed (lucerne hay and faba beans, respectively) in the frequency range of 1-5 GHz. The dielectric constant was higher in the case of high moisture percentage sample at low frequency. However, it decreases or remains constant with increasing frequency. A similar result was observed in the previous dielectric study with various types of grain (Nelson 1952).

Table 2 and Table 3 show a subset of the dielectric dataset of different feed types (roughage and concentrate), MW frequency, and moisture content status. Both the dielectric constant (real part) and the loss factor (imaginary part) increased with increasing moisture percentage from oven-dried samples to control, 25%, 50%, 75%, and 100% moisture addition, on a dry matter basis. On the other hand, the dielectric constant and loss factors of roughage and concentrate reduced with increasing frequency (Figure 2).

The dielectric properties of dry forage hays and grains are very low due to the low moisture content. The presence of moisture in the material is the major factor that determines the dielectric behavior of the material (Nelson 1981). The increase in the dielectric value of forage hays and grains with increasing moisture content agreed with previous studies. Ulaby et al. (1984) showed an increase in the dielectric properties in wheat and maize leaves and stalk after they were extracted from the plants, and moisture was added separately. Another study with various grains (barley, wheat, corn, and barley) revealed that the dielectric constant increased with increasing grain moisture content at any frequency. However, the measurement was done with very low

frequencies, from 1 MHz to 50 MHz, in that study. Another study with various types of grain (red winter wheat, sorghum, spring oats, soybean, and alfalfa/lucerne) was measured from low frequency (250 Hz) to very high frequency (12 GHz) (Nelson and Stetson 1975). The study showed that dielectric constant and loss factors decreased with increasing frequency (Nelson and Stetson 1975).

An unusual fluctuation in the dielectric loss factor of wheat forage hay and maize grain was observed, after some time, with increasing frequency. However, the reason behind that is unknown. A possible assumption could be due to the improper fitting of the open-ended coaxial probe of vector network analyzer on the sample under test.

Table 2. A subset of dielectric data as a function of roughage, frequency, and feed sample moisture status.

Forage hay type	Frequency ($\times 10^9$ Hz)	Moisture status (Moisture added on dry matter basis)											
		Control		Oven dried		25%		50%		75%		100%	
		e'	e''	e'	e''	e'	e''	e'	e''	e'	e''	e'	e''
Lucerne	1.0-1.95	1.293	0.007	1.188	0.001	2.903	0.321	3.712	0.769	4.260	1.162	6.848	2.030
	2.0-2.95	1.260	0.023	1.160	0.018	2.770	0.113	3.556	0.337	4.118	0.522	6.754	0.812
	3.0-3.95	1.249	0.055	1.153	0.040	2.717	0.059	3.509	0.050	4.092	0.144	6.784	0.097
	4.0-5.00	1.236	0.077	1.140	0.054	2.696	0.206	3.509	0.166	4.115	0.146	6.909	0.424
Canola	1.0-1.95	1.275	0.001	1.122	0.005	1.457	0.047	2.444	0.433	4.002	1.159	6.459	2.624
	2.0-2.95	1.247	0.031	1.098	0.007	1.412	0.001	2.345	0.184	3.836	0.541	6.263	1.300
	3.0-3.95	1.239	0.064	1.091	0.023	1.399	0.047	2.318	0.017	3.791	0.160	6.227	0.562
	4.0-5.00	1.233	0.088	1.085	0.030	1.393	0.077	2.319	0.101	3.809	0.104	6.288	0.066
Pasture	1.0-1.95	1.217	0.016	1.233	0.005	1.830	0.124	2.461	0.391	3.260	0.588	4.831	1.200
	2.0-2.95	1.188	0.010	1.209	0.033	1.761	0.029	2.357	0.166	3.167	0.188	4.730	0.456
	3.0-3.95	1.178	0.039	1.200	0.064	1.741	0.052	2.324	0.008	3.153	0.071	4.728	0.004
	4.0-5.00	1.171	0.050	1.193	0.082	1.731	0.112	2.320	0.104	3.171	0.264	4.787	0.318
Oat	1.0-1.95	1.415	0.017	1.176	0.000	2.219	0.273	2.214	0.285	2.630	0.167	9.144	3.773
	2.0-2.95	1.385	0.028	1.155	0.017	2.124	0.119	2.142	0.112	2.562	0.039	8.776	2.063
	3.0-3.95	1.379	0.086	1.155	0.048	2.095	0.013	2.125	0.027	2.556	0.222	8.664	1.079
	4.0-5.00	1.372	0.116	1.147	0.055	2.083	0.096	2.122	0.111	2.573	0.352	8.686	0.427
Wheat	1.0-1.95	1.111	0.002	1.165	0.016	1.429	0.044	3.014	0.148	3.376	0.385	3.927	0.437
	2.0-2.95	1.102	0.008	1.156	0.014	1.402	0.002	2.939	0.059	3.289	0.085	3.839	0.033
	3.0-3.95	1.102	0.027	1.159	0.040	1.399	0.040	2.928	0.246	3.280	0.145	3.840	0.270
	4.0-5.00	1.101	0.036	1.151	0.054	1.391	0.070	2.943	0.397	3.298	0.316	3.881	0.503
Rice straw	1.0-1.95	1.216	0.035	1.151	0.040	1.641	0.013	3.136	0.118	3.691	0.114	4.695	0.220
	2.0-2.95	1.181	0.012	1.119	0.018	1.624	0.050	3.101	0.133	3.649	0.168	4.632	0.178
	3.0-3.95	1.176	0.030	1.118	0.019	1.617	0.099	3.104	0.327	3.658	0.399	4.652	0.491
	4.0-5.00	1.167	0.026	1.108	0.010	1.621	0.156	3.144	0.508	3.715	0.607	4.731	0.756

As shown in Figure 2, moisture had the most profound effect on both the dielectric constant (ϵ') and the loss factor (ϵ'') of the roughage and concentrate samples. For example, at 2450 MHz, the dielectric constant of lucerne increases from 1.13 to 6.72 as the moisture content increases from oven dry to 100 % (w/dry w), and the loss factor increases from 0.008 to 0.81.

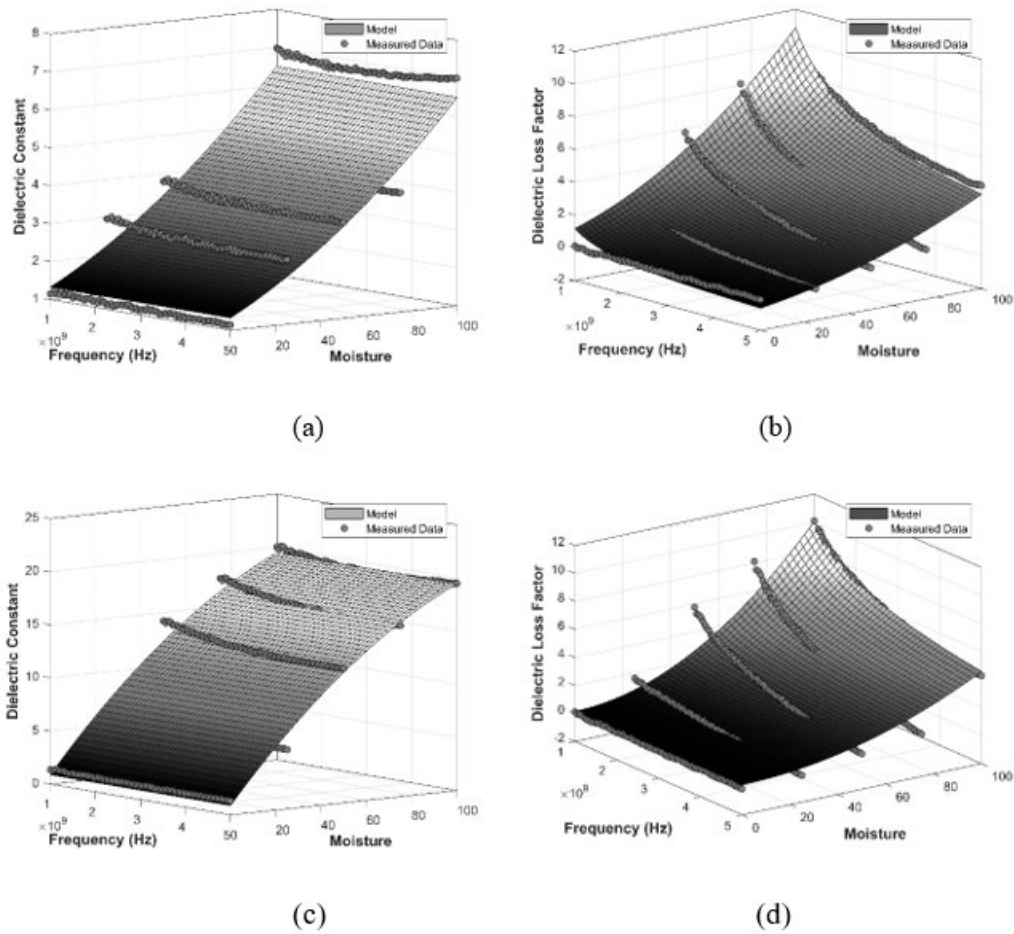


Figure 2: The (a), (c) real part and (b), (d) imaginary part of the dielectric properties of lucerne hay and faba bean respectively as a function of frequency and moisture content

For any moisture content, the dielectric constant does not significantly change with frequency; however, the loss factor reduces with increasing frequency. For example, at 100 % moisture content, the loss factor for faba bean changes from 10.1 at 1000 MHz to

4.3 at 5000 MHz. This decline in loss factor is probably due to a combination of the frequency response of bound water in the samples and ionic conduction at low frequencies.

Table 3. A subset of dielectric data as a function of concentrate feeds, frequency, and feed sample moisture status.

Concentrate type	Frequency ($\times 10^9$ Hz)	Moisture status (Moisture added on dry matter basis)											
		Control		Oven dried		25%		50%		75%		100%	
		e'	e''	e'	e''	e'	e''	e'	e''	e'	e''	e'	e''
Faba bean	1.0-1.95	1.683	0.036	1.375	0.011	6.344	1.255	13.750	4.332	17.220	6.065	19.741	5.598
	2.0-2.95	1.661	0.114	1.330	0.035	5.886	0.754	13.015	2.578	16.427	3.652	19.263	3.081
	3.0-3.95	1.655	0.179	1.327	0.087	5.678	0.352	12.691	1.534	16.089	2.277	19.148	1.687
	4.0-5.00	1.659	0.242	1.324	0.098	5.591	0.037	12.608	0.782	16.057	1.344	19.342	0.748
Wheat grain	1.0-1.95	1.787	0.011	1.524	0.013	3.915	0.419	8.789	1.175	14.851	3.389	24.200	4.206
	2.0-2.95	1.735	0.079	1.482	0.072	3.689	0.215	8.298	0.599	13.974	2.186	23.166	2.655
	3.0-3.95	1.724	0.165	1.478	0.137	3.588	0.015	8.094	0.095	13.596	1.353	22.808	1.564
	4.0-5.00	1.720	0.218	1.476	0.165	3.546	0.140	8.041	0.292	13.497	0.762	22.867	0.827
Maize	1.0-1.95	1.687	0.033	1.370	0.028	2.208	0.016	2.759	0.094	5.101	0.321	6.548	0.342
	2.0-2.95	1.648	0.029	1.322	0.020	2.170	0.116	2.723	0.264	4.971	0.004	6.440	0.119
	3.0-3.95	1.641	0.091	1.315	0.069	2.172	0.217	2.740	0.432	4.961	0.281	6.477	0.492
	4.0-5.00	1.639	0.139	1.310	0.077	2.180	0.300	2.771	0.572	5.000	0.495	6.575	0.768

The same model can also describe the other roughages' and concentrate feeds' dielectric properties, with comparable goodness of fit.

Table 4: Model parameters for the real part of the dielectric constant of various grains

Parameter	Feed types								
	Roughage (forage hay and straw)						Concentrate		
	Lucerne	Canola	Pasture	Oat	Wheat	Rice straw	Faba bean	Wheat	Maize
ϵ_{dr}	0.902	0.959	0.941	0.701	0.645	0.311	0.837	0.250	0.246
ϵ_{∞}	0.431	0.150	0.336	0.967	0.347	0.705	0.047	0.353	0.938
ϵ_s	2.985	0.410	1.050	4.390	4.040	0.930	11.09	1.198	1.280
f_o (Hz)	3.277×10^5	0.843	0.124	5.242×10^6	6.22	0.308	1270	0.568	0.211
b	0.065	-0.021	0.024	-0.058	0.102	0.006	5.104	0.211	0.026
c	0.001	0.004	0.001	0.001	0.000	0.001	-0.015	0.004	0.000
r^2	0.95	0.99	0.99	0.87	0.94	0.85	0.98	0.99	0.98

Table presents the model parameters for the real parts of the dielectric properties for three grains and six forages.

Table presents the additional model parameters for the imaginary part of the same materials' dielectric properties. It is unclear why the moisture function parameters are so different between the real and imaginary models; however, the other parameter values of ϵ_{∞} , ϵ_s and f_0 are the same.

It is also apparent that the model fits the real part of the dielectric properties very well; however, the model does not fit the imaginary part of the dielectric properties quite as well, especially for the forage samples. This may be due to the inherent error associated with using a dielectric probe to extract the imaginary portion of the dielectric constant (Brodie G et al. 2016). It may also be due to poor coupling between the surface of the dielectric probe and the material under test.

Table 5: Model parameters for the imaginary part of the dielectric constant of various grains

Parameter	Feed types								
	Roughage (forage hay and straw)						Concentrate		
	Lucerne	Canola	Pasture	Oat	Wheat	Rice straw	Faba bean	Wheat	Maize
ϵ_{di}	-0.751	0.000	-0.492	-0.460	-0.417	-0.481	0.000	0.000	0.000
σ	0.091	0.029	0.056	0.092	0.049	0.061	0.043	0.024	0.024
b	-0.236	4054	-294.8	0.269	4.151	2335	-2.581	228.1	1155
c	-0.002	-70.47	-10.94	-0.004	-0.079	-10.11	-0.079	-30.67	-150.2
r^2	0.78	0.71	0.73	0.73	0.59	0.59	0.93	0.81	0.83

Figure 3 presents examples of the electromagnetic penetration depth in lucerne and faba beans. In both cases, the penetration depth is highest at low frequencies in the dry material and least at high frequencies in wet material; however, there are clear differences in the rate at which the penetration depth diminishes as a function of frequency and moisture content between the two feeds.

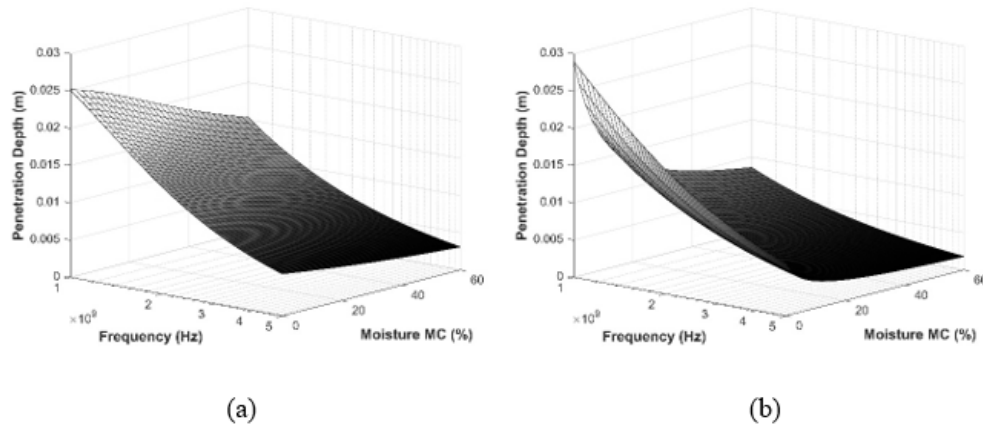


Figure 3: Electromagnetic penetration depths of (a) lucerne and (b) faba bean as a function of frequency and moisture content

These differences are directly associated with the differences in the dielectric properties of the two materials. That same would be expected with all the other feed materials tested during this study.

Conclusion

The data in this study clearly represents the impact of the feed samples' moisture content on the feeds' dielectric properties. In addition, an applicable mathematical model has been developed to predict the complex dielectric properties of different roughage and concentrate feeds at different moisture contents and frequencies within the studied frequency range. This model will help identify the proper frequency response of the feed material for further processing with MW treatment technology.

Funding

N/A

Disclosure statement

There is no conflict of interest to report for this research work

Reference

- AOAC. 1990. Official methods of analysis of the Association of Official Analytical Chemists
Arlington: AOAC International.
- Bhattacharya M, Basak T. 2017. A comprehensive analysis on the effect of shape on the
microwave heating dynamics of food materials. *Journal of Innovative Food Science Emerging
Technologies*. 39:247-266.
- Brodie, Natalie Bootes, Frank Dunshea, Leury B. 2019. Microwave Processing of Animal Feed: A
Brief Review. *Transactions of the ASABE*. 62(3):705-717.
- Brodie, Rath C, Devanny M, Reeve J, Lancaster C, Doherty T, Harris G, Chaplin S, Laird C. 2012.
The Effect of Microwave Treatment on Animal Fodder. *Journal of Microwave Power and
Electromagnetic Energy*. 46(2):57-67.
- Brodie G, Jacob M, Farrell P. 2016. Microwave and Radio-Frequency Technologies in Agriculture:
An Introduction for Agriculturalists and Engineers. Warsaw/Berlin: De Gruyter Open Ltd.
- Brodie GI. 2008. Innovative wood drying: Applying microwave and solar technologies to wood
drying. VDM Publishing.
- Brusewitz GH, Pitt RE, Chase LE, Collins M, Delwiche SR, Garthe JW, Muck RE. 1993. Forage
Moisture Determination (NRAES 59). Northeast Regional Agricultural Engineering Service
(NRAES).
- Chandrasekaran S, Ramanathan S, Basak T. 2013. Microwave food processing—A review. *Food
Research International*. 52(1):243-261.
- Cole KS, Cole RH. 1941. Dispersion and Absorption in Dielectrics. I. Alternating Current
Characteristics. *Journal of Chemical Physics*. 9(4):341-351.
- Debye P. 1929. Polar Molecules. New York: Chemical Catalog.
- Dong S, Long R, Zhang D, Hu Z, Pu X. 2005. Effect of microwave treatment on chemical
composition and in sacco digestibility of wheat straw in yak cow. *Asian-Australasian Journal of
Animal Sciences*. 18(1):27-31.
- Esch M, Sukhorukov VL, Kürschner M, Zimmermann UJBORoB. 1999. Dielectric properties of
alginate beads and bound water relaxation studied by electrorotation. *Biopolymers*. 50(3):227-
237.
- Higgins T, Spooner A. 1986. Microwave drying of alfalfa compared to field-and oven-drying:
Effects on forage quality. *Animal feed science and technology*. 16(1-2):1-6.
- Kabir H, Khan MJ, Brodie G, Gupta D, Pang A, Jacob MV, Antunes E. 2020. Measurement and
modelling of soil dielectric properties as a function of soil class and moisture content. *Journal of
Microwave Power and Electromagnetic Energy*. 54(1):3-18.
- Mahyuddin P, Little D, Lowry J. 1988. Drying treatment drastically affects feed evaluation and
feed quality with certain tropical forage species. *Animal feed science and technology*. 22(1-
2):69-78.
- Metaxas Aa, Meredith RJ. 1983. Industrial microwave heating. IET. 4).
- Nelson S. 1952. A method for determining the dielectric properties of grain [M. Sc. Thesis].
- Nelson S. 1981. Review of Factors Influencing the Dielectric Properties of Cereal Grains'. *Journal
of Cereal Chemistry*. 58(6):487-492.
- Nelson S, Stetson LJTotA. 1975. 250-Hz to 12-GHz dielectric properties of grain and seed.
18(4):714-0715.
- Park Y, Anderson M, Walters J, Mahoney A. 1983. Effects of processing methods and agronomic
variables on carotene contents in forages and predicting carotene in alfalfa hay with near-
infrared-reflectance spectroscopy. *Journal of dairy science*. 66(2):235-245.
- Puligundla P, Abdullah S, Choi W, Jun S, Oh S, Ko S. 2013. Potentials of microwave heating
technology for select food processing applications-a brief overview and update. *Journal of Food
Processing & Technology*. 4(11):1-9.
- Sadeghi A, Nikkhah A, Shawrang P. 2005. Effects of microwave irradiation on ruminal
degradation and in vitro digestibility of soya-bean meal. *Animal Science*. 80(3):369-375.

432 Sadeghi A, Shawrang P. 2006. Effects of microwave irradiation on ruminal degradability and in
 433 vitro digestibility of canola meal. *Animal feed science and technology*. 127(1-2):45-54.
 434 Sadeghi A, Shawrang P. 2008. Effects of microwave irradiation on ruminal dry matter, protein
 435 and starch degradation characteristics of barley grain. *Animal feed science and technology*.
 436 141(1-2):184-194.
 437 Taheri S, Brodie G, Jacob MV, Antunes E. 2018. Dielectric properties of chickpea, red and green
 438 lentil in the microwave frequency range as a function of temperature and moisture content.
 439 *Journal of Microwave Power and Electromagnetic Energy*. 52(3):198-214.
 440 Trabelsi S, Paz AM, Nelson SO. 2013. Microwave dielectric method for the rapid, non-destructive
 441 determination of bulk density and moisture content of peanut hull pellets. *J Biosystems*
 442 *engineering*. 115(3):332-338.
 443 Ulaby, Jedlicka R, Sensing R. 1984. Microwave dielectric properties of plant materials. *Journal of*
 444 *IEEE Transactions on Geoscience*.(4):406-415.
 445 Ulaby FT, El-Rayes MA. 1987. Microwave Dielectric Spectrum of Vegetation - Part II: Dual-
 446 Dispersion Model. *IEEE Transactions on Geoscience and Remote Sensing*. GE-25(5):550-557.
 447