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Frequency, Temperature and Moisture Dependent Dielectric Properties of Chicken Manure Relevant to Radio frequency/Microwave Drying

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Abstract
Dielectric properties (dielectric constant & dielectric loss factor) of chicken manure in the temperature range of 10-70 °C and moisture contents of 15%, 25%, 35%, and 40% (wet basis), were determined using Agilent high temperature open-ended coaxial probe coupled with vector network analyzer in the frequency range 10 MHz to 14 GHz. It is observed that the dielectric constant and dielectric loss factor decrease with an increase of frequency at all temperatures. Moreover, these properties increase smoothly with temperature and moisture content up to ~40 °C, and beyond it, values increase abruptly at all frequencies. The penetration depths of the electromagnetic field in chicken manure samples were calculated at ISM (industrial, scientific and medical) frequencies of 13, 27, 40, 915, 2450, and 5800 MHz by making use of measured dielectric properties and it was observed that these depths decrease with increase in frequency at all moisture content and temperatures. The data of dielectric properties and penetration depths presented in this paper helps to develop the radio frequency/microwave applicators for providing dielectric heat treatment to chicken manure for various applications such as drying, disinfestation, pasteurization etc.

Introduction
Chicken manure, which is considered a bio-waste could be a possible option to scientists and government agencies looking for an effective, economical and safe alternative to non-renewable energy resources (Chastain and Coloma-Del Valle, 2008). Chicken manure is poultry excreta containing feathers, undigested feed and bedding material (Chastain *et al*., 2012). In 2019, net production of poultry meat was forecasted to be 128 million metric tons, with an increase of 3% in comparison to 2018 (Conway, 2019). These global trends suggest significant growth in chicken manure production.

The major application of chicken manure is to use in croplands as an alternative to commercial fertilizers due to high pH, low organic carbon/nitrogen ratio (Araji *et al.*, 2001; Williams, 2013), more residual value than urea (Bolan *et al.*, 2010) and higher plant-available nitrogen content than other animals' manure (Jones, 2006). It can also be considered a feedstuff for fish and ruminants (Martin *et al*., 1983; Al-Masri, 1998; Han, 2013), and a critical biofuel used in other industries (Schnitzer *et al*., 2007; Billen *et al*., 2015; Baki Unal *et al*., 2015). Fresh chicken manure contains more than 60% of water and cannot be used directly because a large amount of water does not allow uniform spreading. It can also lead to odor, fly, and pathogen problems. Further, direct fertilizing may pollute soil, groundwater and also increases cost of transportation (Aboltins and Kic, 2014). Another limitation is its seasonal application in many areas across the globe (Hollis, 2002; Pelton, 2012). Finally, approximately 15% of moisture content is enough to achieve maximum heat during burning (Jones, 2006).

The most reasonable solution to combat wet chicken manure problems is to dry it and reduce its water content to the required level (Ghaly and Alhattab, 2013; Aboltins and Kic, 2014). Drying chicken manure effectively solve the environmental and health issues, reduces manure's weight, and thus minimize the storage space, transportation cost

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(Stronga, 2018). Drying of chicken manure can be achieved by several methods including natural air drying using deep pits, in-house slat drying system, in-house belt system, and mechanical drying systems. Natural air drying using deep pits is not recommended because of slow drying rate and high nutrient loss. In addition, drying by this method is not possible in winters and in cold countries. For in-house slat drying, slats have to be purchased, constructed and then emptied every 6 months. In-house belt system requires more energy for drying and is also labor intensive. It is costly to buy and build this drying system. Mechanical drying systems have a relatively high cost of equipment and drying energy. More time and energy may be required for the transportation of manure from and to mechanical dryers. In addition, mechanical drying plants cause air pollution and may be affected by regulatory restrictions (Canada Poultry Section, 1990).

Seeing the numerous drawbacks of existing drying systems, an environmentally friendly, cost-effective, energy-efficient, and new technology-based approach is required to work at industrial scale. One such idea is to use radio/microwaves for drying chicken manure which is called dielectric heating. Radio (1 KHz-300 MHz) and microwaves (300 MHz-300 GHz) represent adjacent bands in electromagnetic (EM) spectra. The international community agrees upon their use for heating/drying purposes at some specific frequencies of ~13, 27, 40, 915, 2450; 5800 MHz called ISM frequencies, to avoid interference with telecommunication. Such heating is called dielectric heating/drying, which is already employed in the food and agriculture industry (Venkatesh and Raghavan, 2004; Wang *et al*., 2011), textile drying, paper industry, wood processing (Agrawal *et al*., 2008), and ceramic industry (Das *et al*., 2009). Dielectric dying is superior to conventional drying methods because it is rapid, has volumetric energy dissipation, moisture level automation, and is best suited controlling the quality of final product (Jones and Rowley, 1996). Such radio and micro wave drying is possible if dielectric properties of chicken manure are known at different moisture levels and temperatures corresponding to ISM heating frequencies.

Dielectric properties of any material is generally expressed by complex permittivity and it is given by $\varepsilon^* = \varepsilon' - j\varepsilon''$ where ε' is the dielectric constant which is a measure of energy storage) , $j = \sqrt{-1}$ and ε'' represents the dielectric loss factor which determines energy loss in the material (Nelson, 1973). This loss of electromagnetic energy in dielectric material raises the temperature of the material through the following energy balance expression:

$$\rho C_p \frac{dT}{dt} = 55.63 \times 10^{-12} f E^2 \varepsilon''$$

Where ρ, $\frac{dT}{dt}$, C_p are density (in kg/m^3), temperature rise per second ($°C\ s^{-1}$) and specific heat (in J kg^{-1} $°C^{-1}$) of the material, respectively. f and E are frequency (in Hz) and rms electric field intensity (in V/m^{-1}) of incident electromagnetic field (Sosa-Morales *et al*., 2010).

The objectives of the present work are: a) to determine the broadband dielectric properties of chicken manure samples in the frequency range of 10 MHz - 14 GHz, at moisture contents of 15, 25, 35, 40% (wet basis; w. b) and in the temperature range of 10-70 °C , b) to model the acquired data of dielectric properties in term of fitted polynomials at specific ISM frequencies of 13, 27, 40, 915, 2450 and 5800 MHz, and c) to calculate the penetration depths of the electromagnetic field at these ISM frequencies in chicken manure sample.

Materials and Methods

Manure sampling

Broiler chicken manure in lump form was collected in polythene bags from a local poultry farm in Longowal (Punjab, India). To obtain representative samples, manure was collected in a zig-zag pattern within the poultry farm. Samples were allowed to dry on plastic sheets in sunlight for 3 days to restrict any insects growth. They were also covered with thin porous sheets so that other foreign particle and dust could not enter the sample. Dried chicken manure sample was then crushed and grinded manually by using an Agate mortar and pestle set till particles become finer in size. Particle size analysis of chicken manure was done by using different sized sieves.

Homogeneous sample obtained by thoroughly mixing chicken manure particles of all sizes less than 250 µm were used for dielectric property measurement. Particles size more than 250 µm was not taken as a maximum size of 300 µm can be used with Agilent high temperature open-ended coaxial probe (HTOCP) for better results (Technologies, 2017).

Moisture content determination and sample preparation

As soon as the chicken manure samples were collected and transported to laboratory, initial moisture content was determined by drying a 10 g sample in a forced-air oven (Thermostat i-therm AI-7781) for 24 h at 103 °C (ASAE, 1991). This was repeated three times and their mean was considered as a true moisture content. Four chicken manure samples with moisture content ~15% (w.b.), ~25% (w.b.), ~35% (w.b.) and ~40% (w.b.) were prepared by adding distilled water slowly into the ~9% (w.b.) sample and each was mixed thoroughly with the help of stirring glass rod. These 4 sets of samples were stored at 10 ℃ in a refrigerator for 12 h. Each sample was equilibrated at room temperature for 6 h before further analysing.

It is important to note that attempts to make a thoroughly mixed homogeneous chicken manure sample having moisture content more than 40% (w.b.) failed repeatedly because added distilled water get separated within 3-4 h and a homogeneous sample preparation could not be achieved which is prerequisite for sample to be measured with Agilent HTOCP (Technologies, 2019).

Determination of density and penetration depth of Chicken manure

Bulk density of chicken manure was determined by taking a box of known dimensions (21 × 37 ×37 cm). Density was calculated for all 4 manure samples.

Penetration depth (D_p) is defined as the depth into the sample when radio/microwave power drops to ~37% of its original value. It is calculated by the equation proposed by Sosa-Morales *et al*., (2010):

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

where c = speed of light (3×10^8 m/s) ; f = frequency of incident radio/micro wave.

Measurement system

A two port vector network analyzer (VNA; Agilent ENA series E5071C) was used to measure the dielectric properties which was connected to an external computer having Agilent material measurement software 85070E and was coupled with Agilent HTOCP. The relative dielectric properties are measured in term of ε' and ε'' which are extracted from the reflection coefficients arising from the reflection of electromagnetic field from the sample closely in contact with probe head. A water circulator with temperature controller (Thermotech TH-012, India) was used to raise the temperature of the sample by circulating the water through jacket of sample holder with the help of high-density rubber foam insulation pipes. The temperature of the sample was measured by using thermocouple (DTM 3000-Spezial LKM Electronics, GmbH). Whole arrangement was in accordance with Bansal *et al*. (2015) report. Entire measurement system was kept fixed on a table and free from any surrounding vibrations so as to minimize any kind of errors.

Procedure

Laboratory was maintained at a temperature of 23°C and VNA was kept standby for 2 h to remove any sort of drift errors. Electronic calibration module (Agilent N4691) was used for calibration purpose and a standard sequence of open (air), short and distilled water at 23°C was followed for complete calibration. Dielectric measurements were taken at 1600 discrete frequency on log scale basis for each chicken manure sample by varying the temperature from 10 to 70°C. A total of 3 repetitions were taken for each sample with the same moisture content and average value was considered as true. On similar basis, samples for all moisture contents were measured.

Results and Discussion

Density, particle size, and moisture content

The bulk density of the chicken manure samples was found to be 0.374 g/cm^3 for 15% (w. b.), 0.468 g/cm^3 for 25% (w. b.), 0.513 for 35% (w. b.), and 0.537 g/cm^3 for 40% moisture contents, respectively as shown in Figure 1(a). This increasing trend with moisture content is in agreement with earlier results (Virk *et al*., 2013); however, a small variation may be due to geographical differences of chicken manure site. Total volume of the sample holder was 15.54 cm^3 (internal diameter: 2.17 cm, height: 4.2 cm). Manure sample was filled up to a fixed volume of 10.36 cm^3 (sample holder height of 2.8 cm) which is sufficient to get a semi-infinite volume (Gabriel, 1993) of chicken manure for HTOCP .

The powder form of samples had a different bulk density than those of original samples at the same moisture content. These prepared samples were tapped in a fixed volume of 10.36 cm^3 as shown in Figure 1(b) and some weight was also put upon accordingly to get the density equal to bulk density of original samples in lump form (Table 1).

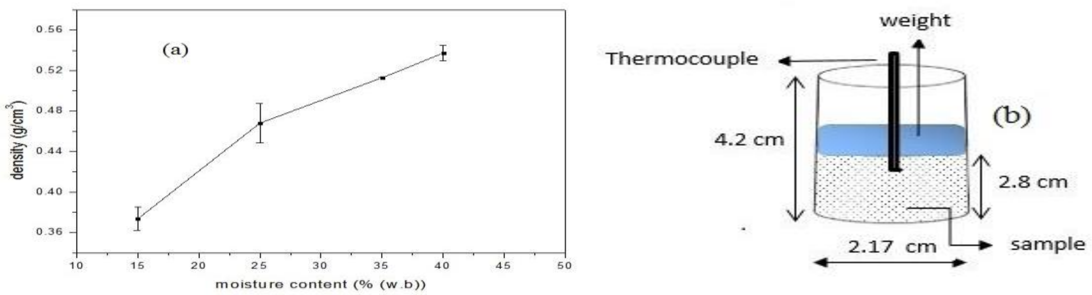

Figure 1. (a) Variation of bulk density with moisture content (b) Sample holder arrangement for using a fixed volume and putting on additional weight

Bulk density of chicken manure in lump form is described by following equation:

$$\rho = 0.289 + 0.0063\,\mathrm{M}; \qquad (\mathrm{R}^2 = 0.964, 15 \le M \le 40)$$

where ρ is density in g/cm^3 and M is moisture content in % (w. b.)

Table 1. Amount of mass (g) to be added in 10.36 cm^3 volume and weight to be put upon sample to obtain original bulk density at different moisture contents

Moisture Content (%)	Bulk density (g/cm^3)	Mass to be added (g)	~Weight to be put (g)
15	0.374	3.8746	90
25	0.468	4.8484	150
35	0.513	5.3147	300
40	0.537	5.5633	400

Using sieve method, particle size analysis indicated that ~28% of particles were less than 106 µm, and ~17% of them were in the range of 106-150 µm, ~26% of them were in range of 150-250 µm, ~18% of them were in the range of 250-500 µm, and ~11% of them were more than 500 µm. Fresh chicken manure possessed a moisture content of 63.71% (w.b.). However, the moisture content of the dried and manually ground sample was ~9% (w.b.).

Dielectric properties

Dielectric properties of chicken manure mainly result from the interaction of radio/micro waves with different constituents of chicken manure such as free water, bound water, protein, ions, and minerals etc. These interactions give rise to different mechanisms like free water dispersion, bound water dispersion and ionic conduction in a broad frequency ranging from10 MHz to 14 GHz (Schwan, 1994; Feng *et al*., 2013) . The dielectric behavior of these components is complex and represented in terms of dielectric constant and loss factor. Semi-log plots have represented these parameters as a function of frequency, temperature, and moisture contents which include 6 radio/micro wave frequencies of 13 MHz, 27 MHz, 40 MHz, 915 MHz, 2.45 GHz and 5.8 GHz.

Figures 2 and 3 show the behavior of ε' and ε'' in the frequency range 10 MHz-14 GHz from 15% (w. b.) to 40% (w. b.) at the temperature range 10-70 °C. It was observed that both ε' and ε'' of chicken manure sample decreases considerably from 10 MHz to 1 GHz and this change is comparatively small as frequency increases from 1 GHz onward. Dependency of the dielectric loss factor on frequency is more regular than that of the dielectric constant. The frequency dependence of chicken manure is similar to measurements done by previous researchers (Nelson and Trabelsi, 2006; Zhuang *et al*., 2007) on other biological materials.

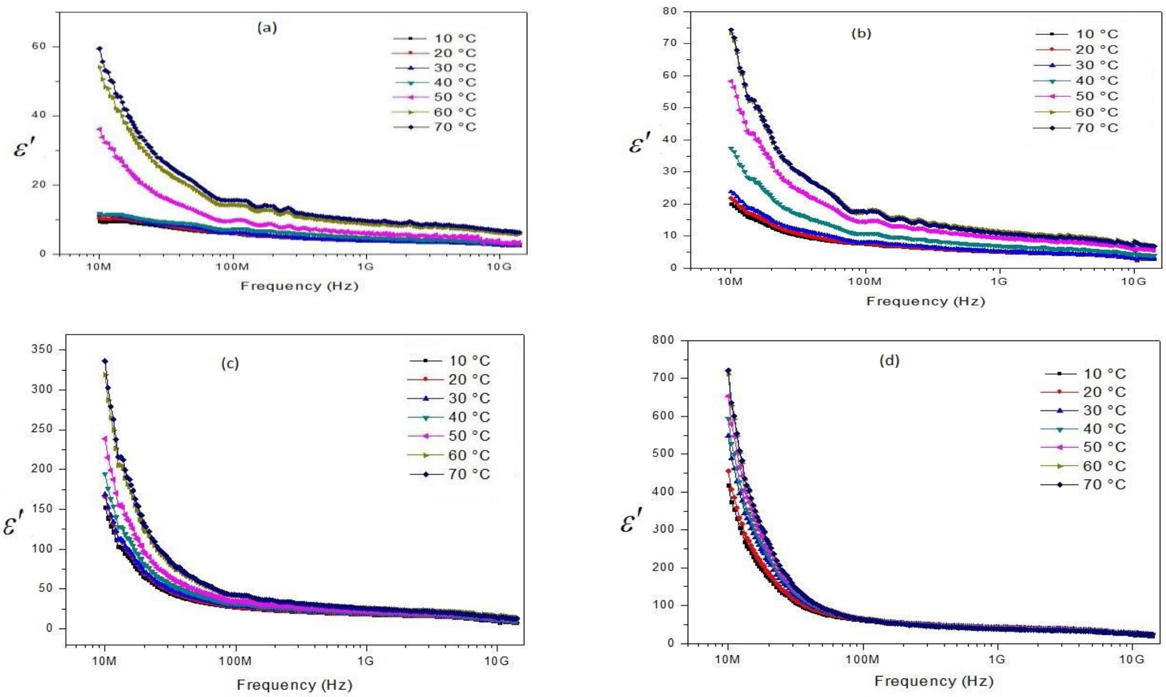

Figure 2 Variation of dielectric constant as a function of frequency and temperature for moisture content. (a) 15%, (b) 25%, (c) 35%, and (d) 40% (w.b.)

Table 2. Coefficients of regression equation to calculate ε' and ε'' at ISM frequencies

f (MHz)		a_0	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}	a_{12}	a_{13}	a_{14}
13	ε'	-446.218	44.4362	-76.24×10^{-2}	-32.77×10^{-3}	86.34×10^{-5}	14.5958	-1.00387	22.48×10^{-3}	-66.83×10^{-6}	-34×10^{-2}	94.41×10^{-4}	-14×10^{-5}	51×10^{-4}	-20×10^{-6}	-32.61×10^{-6}
	ε''	-1999.94	190.49	-3.33	-14.03×10^{-2}	38.7×10^{-4}	168.924	-16.42	58.66×10^{-2}	-62.81×10^{-4}	-2.53718	37.55×10^{-3}	-51.61×10^{-5}	51.15×10^{-3}	-11.08×10^{-5}	-35.06×10^{-5}
27	ε'	-179.49	19.1045	-34.86×10^{-2}	-14.4×10^{-3}	39.29×10^{-5}	5.91833	-49.586×10^{-2}	15.19×10^{-3}	-12.41×10^{-5}	-11.98×10^{-2}	29.67×10^{-4}	-52×10^{-6}	20.39×10^{-4}	-4.31819×10^{-6}	-13.63×10^{-6}
	ε''	-999.419	95.6174	-1.67137	-70.5×10^{-3}	19.42×10^{-4}	83.1062	-8.08388	28.84×10^{-2}	-30.74×10^{-4}	-1.24728	18.59×10^{-2}	-26.65×10^{-5}	25.19×10^{-3}	-50.69×10^{-6}	-17.34×10^{-5}
40	ε'	-103.907	11.5517	-22.02×10^{-2}	-88.26×10^{-4}	25×10^{-5}	4.81541	-48.06×10^{-2}	17.40×10^{-3}	-18.58×10^{-5}	-72.60×10^{-3}	15.83×10^{-4}	-32.16×10^{-6}	13.5×10^{-4}	-1.01548×10^{-6}	-9.40822×10^{-6}
	ε''	-680.952	65.2735	-1.14464	-48.19×10^{-3}	13.29×10^{-4}	56.4066	-5.47608	19.56×10^{-2}	-20.85×10^{-4}	-85.20×10^{-2}	12.34×10^{-3}	-17.89×10^{-5}	17.29×10^{-3}	-33.72×10^{-6}	-11.9×10^{-5}
915	ε'	-41.0393	4.9104	-10.17×10^{-2}	-38.62×10^{-4}	11.63×10^{-5}	1.97068	-22.46×10^{-2}	95.17×10^{-4}	-12.34×10^{-5}	-23.75×10^{-3}	11.04×10^{-5}	-3.17×10^{-6}	56.40×10^{-5}	-3.34837×10^{-7}	-3.99841×10^{-6}
	ε''	-33.5397	3.37655	-60.29×10^{-3}	-24.93×10^{-4}	70.89×10^{-6}	2.80314	-28.66×10^{-2}	10.16×10^{-3}	-10.8×10^{-5}	-36.77×10^{-3}	83.62×10^{-5}	-14.15×10^{-6}	69.98×10^{-5}	-7.20423×10^{-7}	-5.12586×10^{-6}
2450	ε'	-38.5061	4.56964	-94.26×10^{-3}	-35.9×10^{-4}	10.75×10^{-5}	1.72902	-19×10^{-2}	80×10^{-4}	-10.35×10^{-5}	-23.75×10^{-3}	17.34×10^{-5}	-3.47054×10^{-6}	53.42×10^{-5}	-7.52561×10^{-7}	-3.67759×10^{-6}
	ε''	-15.3627	1.64611	-31.93×10^{-3}	-12.25×10^{-4}	37.82×10^{-6}	1.27618	-13.59×10^{-2}	49.50×10^{-4}	-55.51×10^{-6}	-15.52×10^{-3}	42.21×10^{-5}	-7.37974×10^{-6}	28.44×10^{-5}	-1.79949×10^{-7}	-2.1319×10^{-6}
5800	ε'	-32.0561	3.79472	-78.66×10^{-3}	-29.90×10^{-4}	89.59×10^{-6}	1.38341	-13.93×10^{-2}	57.81×10^{-4}	-73.31×10^{-6}	-25×10^{-3}	24.17×10^{-5}	-4.29266×10^{-6}	53.26×10^{-5}	-1.12135×10^{-6}	-3.56758×10^{-6}
	ε''	-12.5055	1.50425	-33.07×10^{-3}	-11.86×10^{-4}	39.26×10^{-6}	95.23×10^{-2}	-11.38×10^{-2}	46.61×10^{-4}	-57.99×10^{-6}	-89.85×10^{-4}	12.67×10^{-5}	-5.48443×10^{-6}	21.58×10^{-5}	1.92254×10^{-6}	-2.08996×10^{-6}

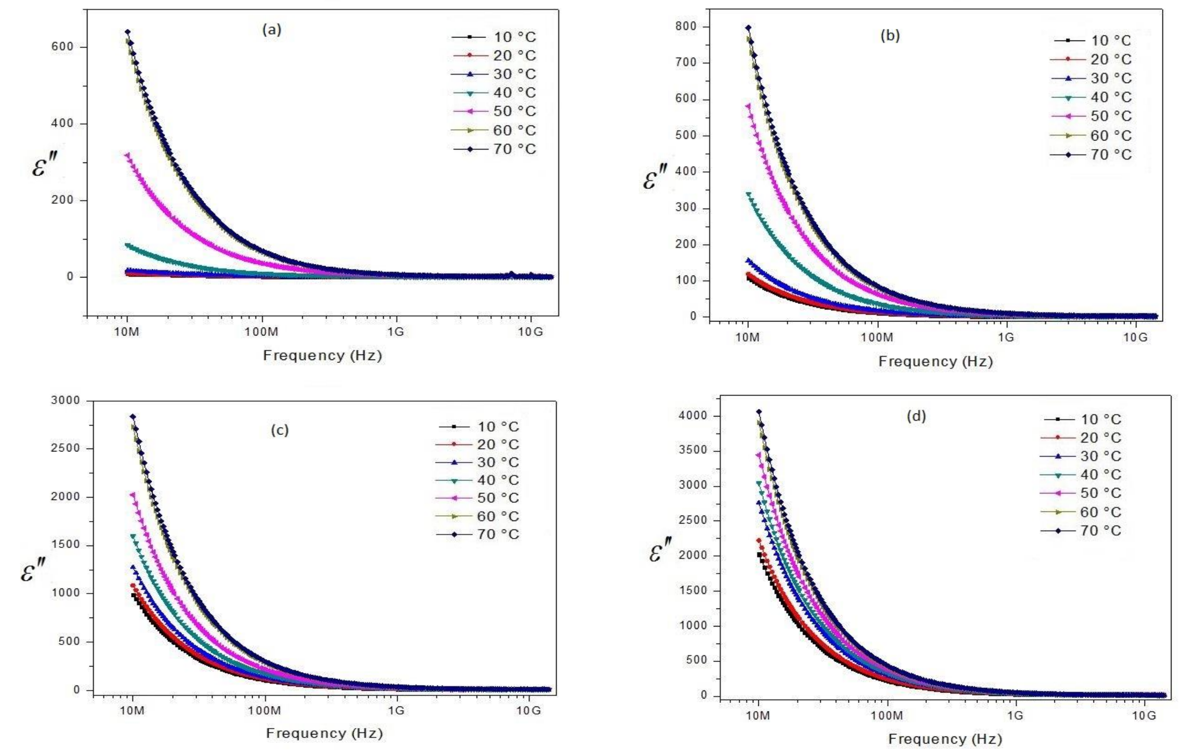

Figure 3.Variation of dielectric loss factor as a function of frequency and temperature for moisture content. (a) 15%, (b) 25%, (c) 35%, and (d) 40% (w.b.)

Dielectric properties increase in the entire temperature range for all the moisture contents. This increase is more evident above 40 ℃, especially for the dielectric loss factor in comparison to the dielectric constant. Likewise, a similar rapid increase over 40 ℃ was observed by Guo *et al*. (2008) for chickpea flour. Below 1 GHz, increase in ionic conduction could be the major reason for increase in dielectric properties with temperature and moisture content, whereas above 1GHz, increase in dipolar polarization may be responsible for such increase in dielectric properties (Nyfors and Vainikainen, 1991; Wang *et al*., 2011). In the present study, the trend observed in the variation of dielectric properties of chicken manure with temperature, moisture content, and frequency, is almost similar to the findings of Nelson (2005) on dielectric properties of some agricultural products in broadband frequency range 200 MHz – 20 GHz. However, to the best of our knowledge, no data are available in the literature regarding the dielectric properties of chicken manure.

It is well established that a little change in moisture content significantly changes the dielectric properties of biological materials due to the properties of water molecules such as tiny size, H-bond making ability and dipolar nature (Bansal *et al*., 2016). Overall, dielectric properties are primarily affected by changes in moisture constant, temperature, and frequency.

Penetration depth

Table 3 shows penetration depth ranges from ~147 to ~3 cm for radio wave frequencies and ~11 to ~0.01 cm for microwave frequencies. Penetration depth decrease with an increase in temperature and moisture content. Lower frequencies (radio waves) have higher penetration depth and vice versa. In return, lower frequencies result in uniform heating while higher frequencies correspond to greater surface heating.

Table 3. Penetration depth corresponding to ISM heating frequencies and temperature 10-70 °C

Moisture content (%)	Temperature (°C)	Penetration depth (cm)					
		Frequency (MHz)					
		13	27	40	915	2450	5800
15	10	146.98	89.88	71.24	10.63	4.73	1.61
	20	139.56	84.54	66.61	9.88	4.61	1.57
	30	95.16	63.43	53.41	8.25	4.17	1.56
	40	35.24	24.83	21.41	5.17	2.91	1.42
	50	17.58	11.97	9.89	2.45	1.57	1.22
	60	12.44	8.53	6.99	2.23	1.52	1.00
	70	8.97	8.39	6.88	2.21	1.48	0.42
25	10	31.31	21.75	18.27	5.08	2.71	1.04
	20	29.86	20.67	17.31	4.75	2.63	0.96
	30	25.67	17.76	14.85	3.93	2.28	0.65
	40	17.03	11.78	9.78	2.61	1.63	0.53
	50	12.95	8.93	7.40	1.95	1.27	0.52
	60	11.24	7.75	6.42	1.69	1.14	0.59
	70	11.01	7.59	6.28	1.60	0.72	0.29
35	10	10.07	6.88	5.66	1.56	0.88	0.36
	20	9.61	6.55	5.39	1.46	0.81	0.34
	30	8.81	6.03	4.97	1.33	0.72	0.32
	40	7.83	5.36	4.42	1.16	0.64	0.30
	50	6.94	4.74	3.90	1.00	0.53	0.27
	60	5.97	4.07	3.35	0.84	0.56	0.30
	70	5.86	4.00	3.28	0.81	0.52	0.19
40	10	7.17	4.88	3.99	1.16	0.65	0.25
	20	6.84	4.64	3.80	1.09	0.60	0.26
	30	6.12	4.14	3.38	0.93	0.57	0.26
	40	5.81	3.93	3.20	0.86	0.54	0.27
	50	5.45	3.68	3.00	0.79	0.50	0.26
	60	5.10	3.45	2.81	0.72	0.50	0.27
	70	4.99	3.38	2.75	0.69	0.03	0.01

Conclusion

Dielectric properties of chicken manure in the broad frequency range of 10 MHz – 14 GHz were measured by varying the moisture content and temperature in the range of 15-40% (w. b.) and 10 – 70 °C, respectively. The measuring system was comprised of a two-port VNA, HTOCP, and water circulator. Dielectric constant and loss factor, both decreased significantly with an increase in frequency for all temperatures and moisture contents however an increasing trend in both was observed with increase in temperature and moisture content for entire frequency range. At ISM frequencies of 13, 27, 40, 915, 2450, and 5800 MHz, the dependency of dielectric properties on temperature and moisture content was represented by the fourth order model,predicting the dielectric properties at any temperature in 10 – 70 °C range and any moisture content in the range 15-40% (w. b.) within an error of 5%. The determined data of dielectric constant, dielectric loss factor, and penetration depth at ISM frequencies can be confidently used to model and develop the efficient radiofrequency/microwave applicators to provide dielectrically generated heat to chicken manure. Since penetration depths at radio frequencies are far higher than that of microwave; therefore, heating systems based on radio frequencies could be more efficient to dry a large volume of chicken manure.

Conflict of Interest

The authors declare no conflict of interest regarding the research, its publication, or authorship.

Data Availability

The data that support the findings of this study are available from the corresponding author on reasonable request.

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