18 Permittivity Measurements and Agricultural Applications

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18.1 Introduction

The electrical characteristics of agricultural materials have been of interest for many years. One of the earliest applications was the correlation noted between the electrical resistance, or conductance, of wheat grain and its moisture content [10]. This relationship was eventually utilized for the development of electrical moisture meters that became commonly used in the grain trade [42]. Later, studies on the use of radio-frequency (RF) instruments for rapidly determining moisture content in wheat and rye were reported [8], and grain moisture meters were developed that were based on the relationships between grain moisture content and the capacitance of parallel-plate or coaxial grain sample holders [42]. Moisture measuring instruments based on both principles of DC conductance and RF capacitance measurements were available for many years and both principles are still in use today, though the convenience and sophistication of such moisture meters are much improved in modern instruments.

With the advent of RF dielectric heating, and later microwave heating, potential agricultural applications were explored, and the need was recognized for data on the dielectric properties, or permittivities, of the agricultural products that were being considered for these applications. In connection with research on RF dielectric heating exposures of grain, a technique was developed for reliable measurement of the dielectric properties of grain, and the method and the first data for grain were reported in 1953 [62]. A few years later, dielectric properties were reported for several different kinds of grain and seed at frequencies between 50 kHz and 50 MHz [24, 34].

Upon recognition that dielectric properties data would be of reference value for moisture meter design and dielectric heating applications, such data for grain and seed were organized and first published by the American Society of Agricultural Engineers in 1966 [2]. These data have been published annually and updated on several occasions. They currently appear in the ASAE Standards 2002 as ASAE D293.2 Dielectric Properties of Grain and Seed [4].

Effectively using the dielectric properties of grain for moisture sensing requires that information be obtained on the influence of other variables on these properties as well. Measurements have been taken over ranges of frequency on a number of types of grain and seed at different moisture levels, bulk densities, and temperatures. Dependence of the dielectric properties of grain on these variables was also summarized for reference purposes [64, 45, 46]. In another study, dielectric properties of corn, wheat, and soybeans were measured at 1 to 200 MHz with respect to factors affecting their use for moisture sensing [20].

Another study of the dielectric properties of wheat, barley, and rice was conducted for purposes of evaluating moisture sensing instrumentation for control of grain dryers [5]. Measurements included frequencies of 0.1, 1, and 10 MHz, and effects of temperature and kernel moisture distribution.

The dielectric properties of grain as well as those of grain-infesting insects were needed in research on RF dielectric heating for potential control of the insects through selective heating of the insects [66], and permittivity data for hard red winter wheat and adult rice weevils were reported for a wide range of frequencies, from 250 Hz to 12 GHz [54].

Permittivity measurements for a wide range of different kinds of grain and seed were also made in connection with studies of dielectric heating exposures for improving the germination of these seeds [65]. These dielectric properties data were also summarized for reference [4].

The potential use of permittivities for quality sensing in fruits and vegetables prompted the measurement of microwave permittivities of several fruits and vegetables for background information on their dielectric properties [43, 47, 85, 57]. Some measurements were taken on fruits of different maturities over the frequency range from 200 MHz to 20 GHz [58].

Of course, many measurements have been reported for food materials in connection with microwave cooking applications, but the scope of this chapter is limited to agricultural products prior to processing for food purposes. Some of the permittivity measurement techniques will be reviewed, and some of the newer dielectric properties data will be presented.

In addition, applications of permittivity or dielectric properties data will be discussed with respect to applications such as RF dielectric or microwave heating for product drying, insect control, seed treatment, and product conditioning. The use of permittivities for quality sensing and grain and seed moisture measurement will be discussed further, and other potential applications will also be mentioned.

18.2 Permittivity Measurements

The permittivity and dielectric properties as used in this chapter are defined as follows:

$$\varepsilon = \varepsilon' - j\varepsilon'' = |\varepsilon| e^{-j\delta} \tag{18.1}$$

where ε is the complex permittivity relative to free space, ε' is the dielectric constant, ε'' is the dielectric loss factor, and δ is the loss angle of the dielectric where $\tan\delta = \varepsilon''/\varepsilon'$. The AC conductivity $\sigma = \omega\varepsilon_0\varepsilon''$ S/m, where $\omega = 2\pi f$ is the angular frequency, with f in Hz, and ε_0 is the permittivity of free space, 8.854×10^{-12} F/m. Hereafter in this chapter, "permittivity" will imply the complex relative permittivity. The dielectric constant is associated with the capability for energy storage in the electric field in the material and the loss factor is associated with energy dissipation in the material or the conversion from electric energy to heat energy. Here, all loss mechanisms, due to both dipole relaxation and ionic conduction, are included in the dielectric loss factor ε''.

18.2.1 Measurement Techniques

The first permittivity measurements on grain samples were obtained by adaptation of the reactance variation technique [19] for use with the Boonton 160A Q-Meter[1] [87], and development of a suitable new sample holder for use with grain and seed samples [62]. The measurement was based on a series resonant circuit and employed the replacement of capacitance lost when a sample was removed from the sample holder by a calibrated variable capacitor in the sample holder, connected in parallel with the sample holder capacitance and the main tuning capacitor of the Q-Meter. The LC resonant circuit was tuned to resonance when the sample was present in the coaxial sample holder. The sample was then removed, and resonance was restored by adjusting the calibrated variable capacitor in the sample holder for this measurement. The Q of the circuit changed also when the sample was removed, and this was taken into account by measuring the change in capacitance (reactance variation) necessary to lower the peak voltage V_m reading across the capacitive portion of the resonant circuit to a chosen reference voltage V on both sides of the resonant peak, both with the sample in the sample holder and with the sample removed. These two capacitance values were then used with the voltage ratios V_m/V to calculate the loss tangent, $\tan\delta$ [62]. Measurements on many grain and seed samples were taken in the frequency range from 1 to 50 MHz with this measurement system and reported [34, 4].

For measurements in the 50 – 250 MHz range, a coaxial-electrode sample holder was designed for use with the Boonton 250-A RX Meter, which consisted of variable frequency oscillators and a modified Schering impedance bridge circuit. The sample holder, with a built-in open-circuit termination, was analyzed as several transmission line sections with lumped-circuit element values determined from measurements on standard materials. By measuring the impedance at the input to the sample holder, the dielectric properties of the grain sample, which filled the sample-holding section of the sample holder, were then calculated directly from the complex impedance [21].

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[1] Mention of company or trade names is for the purpose of description only and does not imply endorsement by the U S Department of Agriculture.

The frequency for permittivity measurement capability for grain samples was then extended to the 200 – 500 MHz range through use of a newly designed coaxial sample holder for use with the General Radio Type 1602-B Admittance Meter. This coaxial sample holder with built-in open-circuit termination to enclose the sample was also modeled as transmission line sections, and lumped-circuit values were determined from measurements on standard materials. The permittivity of the sample in the sample-holding portion was then determined by calculation from the admittance measured at the input to the sample holder [72].

To extend the measurement capability to higher frequencies, the short-circuited transmission line technique of Roberts and von Hippel [71] was utilized with several measurement systems, including the X-band rectangular waveguide [37], 21 mm coaxial line [40], 25.4 mm coaxial line (1 and 3 GHz) and circular waveguide (8.5 GHz) [54], and K-band rectangular waveguide [47]. A general computer program for precise calculation of dielectric properties of high- or low-loss materials from short-circuited waveguide measurements was also developed for use with all of these and other measurement systems [67, 68], which was widely used for many dielectric properties measurements and studies at microwave frequencies.

Free-space measurement systems, consisting of transmitting and receiving antennas connected to a vector network analyzer, with grain and seed samples confined in sample holders between the antennas, were used for permittivity measurements in the 5 – 18 GHz range [27, 80, 83]. Measurements of attenuation and phase shift as the wave traversed the grain or seed layer provided the information needed for calculation of the dielectric properties. The problem of phase ambiguity for samples in which the phase shifted more than 180° was resolved [81], a one-way attenuation of 10 dB in the sample rendered the effects of internal reflections and reflections between the antennas negligible, approximations requiring that $\varepsilon'' << \varepsilon'$ were satisfied, and other techniques were used to improve the accuracy of the measurements [83].

For permittivity measurements on fresh fruit and vegetable tissue at 2.45, 11.7, and 22 GHz, core samples were cut to fit short-circuited coaxial line and rectangular waveguide sample holders [43, 47] and the Roberts and von Hippel short-circuited line technique was used [71] with computation of permittivity by the general computer program for this technique [68]. For broadband permittivity measurements on fruits and vegetables in the 10 MHz - 20 GHz range, open-ended coaxial line measurements with network and impedance analyzers were used [56, 51].

18.2.2 Permittivity Data

Available reliable data for the dielectric properties of agricultural products were tabulated 30 years ago [38]. Included were data for animal tissues, foods, plant material, fruits and vegetables, grain and seed, wood and textiles. This tabulation also listed the frequency for which the dielectric constant, loss factor, loss tangent, and conductivity were listed and, when known, the moisture content, temperature, and specific gravity, or density, of the materials, because these factors all influence the permittivity of agricultural materials. Some of these data were also included in later tabulations [75, 22].

The dielectric properties data for grain and seed, which were deemed useful for reference, as already mentioned, currently provide permittivity data for a reasonably wide range of grain and seed types at frequencies from 1 to 50 MHz [4]. Data are also given for several crops in the audio-frequency range, and models for estimating the dielectric constant at 24°C of several major grain crops and soybeans are given as functions of frequency (20 MHz - 2.45 GHz), moisture content and bulk density of the grain and seed. The most comprehensive data are given for hard red winter wheat in the form of contour plots for ε' and ε'' as functions of frequency and moisture content [45], as shown in Fig. 18.1. Here, it is noted that the behavior of ε' is much more regular with frequency and moisture content than is that of ε''.

Some new data on the frequency and temperature dependence of the dielectric properties of fresh fruits and vegetables have recently been obtained [51]. The typical variation of the dielectric constant and loss factor of fresh avocado is shown in Fig. 18.2. The very high values for ε' at the lower end of the frequency range are no doubt attributable to the polarization contributed by ionic conduction, while the behavior of ε' at the higher end of the frequency range is characteristic of dipolar relaxation. It is evident in Fig. 18.2 that at about 90 MHz the temperature dependence of ε' disappears, and the ionic conduction becomes the dominant mechanism influencing the value of ε' below that frequency. This phenomenon was noted for all the fruits and vegetables at some frequency in the 10 - 100-MHz range.

Data for the permittivity of nine fruits and vegetables are shown for a temperature of 25°C at frequencies of 10 and 100 MHz and 1 GHz in Table 18.1.

Table 18.1. Permittivities of fresh fruits and vegetables at indicated frequencies

Fruit or vegetable	10 MHz		100 MHz		1 GHz	
	ε'	ε''	ε'	ε''	ε'	ε''
Apple	109	281	71	33	64	10
Avocado	245	759	66	89	56	14
Banana	166	834	76	91	65	18
Cantaloupe	260	629	70	72	63	14
Carrot	598	1291	87	157	72	23
Cucumber	123	361	80	39	77	9
Grape	122	570	78	60	73	13
Orange	197	617	78	69	72	14
Potato	183	679	73	77	62	16

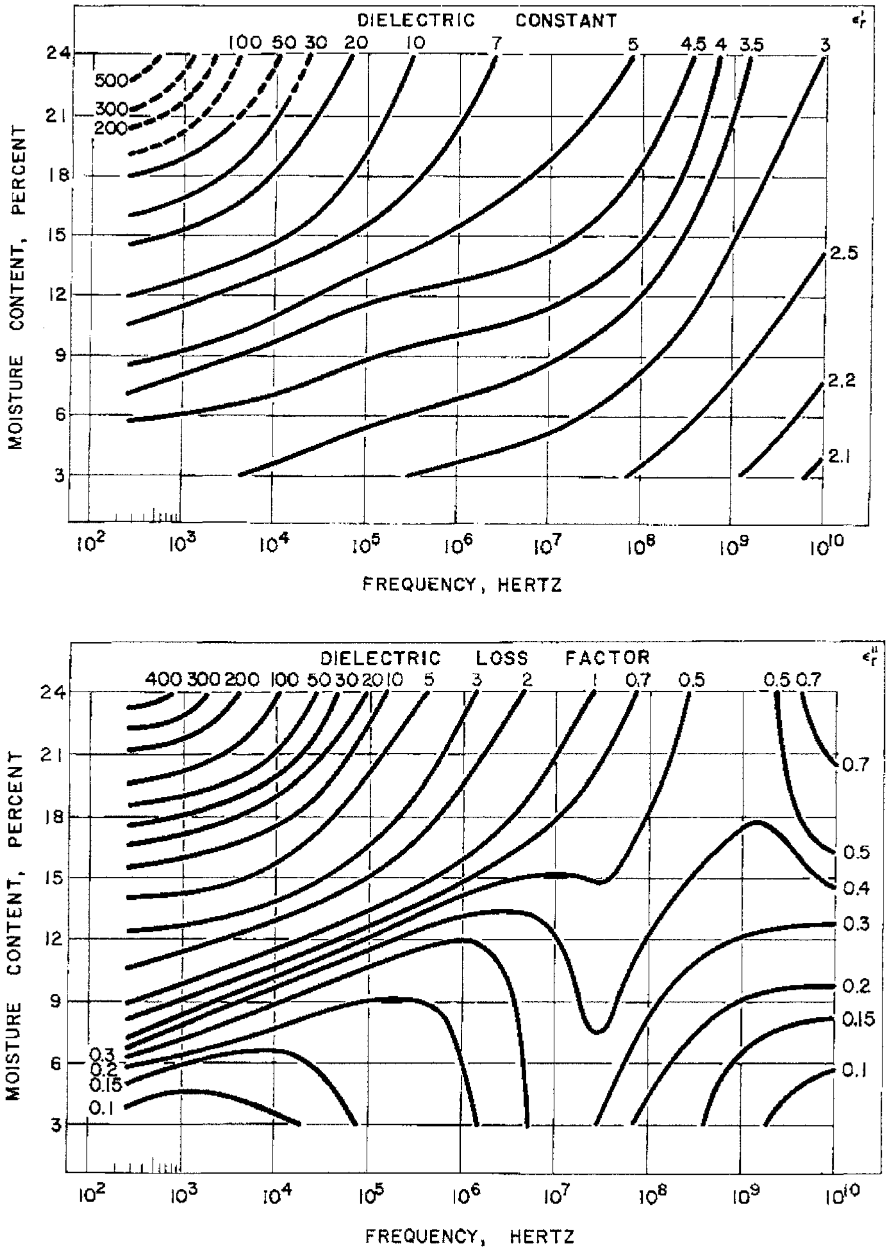

Fig 18.1. Dielectric properties of hard red winter wheat as a function of frequency and moisture content, wet basis, at 24°C [46].

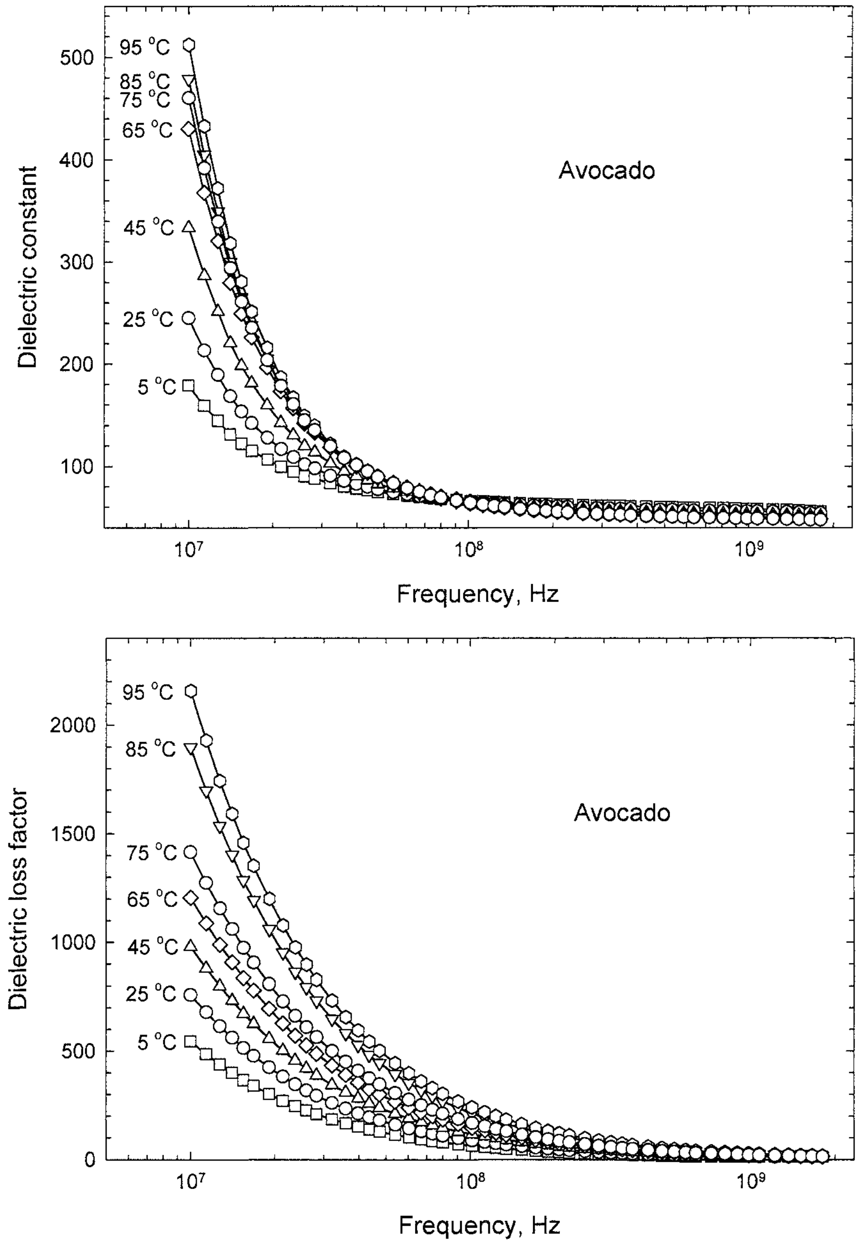

Fig. 18.2. Frequency and temperature dependence of avocado permittivity [51]

The data in Table 18.1 show considerable variation among the different fruits and vegetables. Both real and imaginary parts of the permittivity are particularly large for carrot tissue at the lower frequencies, but these differences largely diminish at microwave frequencies.

Dielectric properties data showing further behavior of these properties with respect to frequency, moisture content, and other variables are summarized elsewhere for grains, fruits, vegetables, and other food materials [48, 55].

18.3 Dielectric Heating Applications

For most agricultural products, the unit value is too small to justify the economic costs of dielectric heating, either at high frequencies or at microwave frequencies. However, if either the speed of heating or an achieved improvement in product quality is sufficiently important, dielectric heating applications might be considered. A few applications will be cited here, but there are probably many more that have been given some consideration.

18.3.1 Product Drying

Drying plant products for safe storage is a common practice in agriculture. As soon as they are sufficiently mature, many must be harvested to avoid potential loss from inclement weather or other undesirable conditions that can develop. If the moisture content of products, cereal grain for example, is too high for short-term storage without spoiling, it must be dried, by circulation either of heated or unheated air through the material. Depending on the product, drying facilities, and the economic environment, the speed of drying can be important. For these reasons studies have been conducted to answer fundamental questions concerning the use of dielectric heating for drying.

Dielectric heating of materials involves the absorption of energy from the high-frequency or microwave electric fields created in the materials and its conversion to heat energy. The power dissipated per unit volume in the material, P, can be expressed as

$$P = 55.63 f E^2 \varepsilon'' \times 10^{-12} \quad \mathrm{W/m^3} \tag{18.2}$$

where f is frequency in Hz, and E is the electric field intensity in the material in V/m. The time rate of temperature, T, rise in the material as a consequence of the power absorption is then

$$dT / dt = 0.239\, P / (c\rho) \quad {}^{\circ}\mathrm{C/s} \tag{18.3}$$

where c is the specific heat of the material and ρ is its specific gravity.

Early research on drying rice with 27 MHz dielectric heating showed promise for continuous drying of rice from field conditions to safe storage levels without damaging milling quality [90]. Experimental high-frequency drying of grain and grass seed at frequencies from 1 to 12 MHz showed improvements in the drying process over conventional methods and that drying could be accomplished at lower temperatures with dielectric heating in combination with heated air drying [24].

Experiments with corn showed that it could be dried much more rapidly by microwave heating at 2.45 GHz than by conventional hot-air drying, but that physical damage to kernels could result if corn was dried too rapidly [17]. Other studies at 2.45 GHz and 915 MHz also showed that speed of drying had to be limited to prevent physical damage to kernels and that this might discourage the use of microwave energy for this purpose. Costs of electricity and equipment for microwave drying in the field were considered too high for practical use.

Microwave heating was investigated for drying seed cotton prior to ginning, but was found impractical [89]. Other studies on microwave and vacuum drying of cotton reduced drying time and was found to improve cottonseed oil marketing properties [1]. Microwave heating under partial vacuum for drying rice and soybeans resulted in products of improved quality, but higher costs have precluded practical use [15].

RF dielectric heating at 43 MHz, with moisture removal by circulation of unheated air, provided rapid drying of chopped alfalfa forage, and resulted in much improved carotene retention without affecting crude protein content [73]. The method could not be recommended for field-drying alfalfa, but did show promise for blanching samples to inactivate carotene-destroying enzymes as an aid in research. Combined microwave and unheated air drying at 2.45 GHz provided rapid drying of laboratory samples of forages and improved quality as well [14]. Such uses of microwave drying have been limited to laboratory and research applications, with costs being too high for consideration of practical-scale use.

18.3.2 Pest Control

Many pests must be dealt with in the production of agricultural crops and in the preservation of agricultural and food products. These include insects, nematodes, fungi, and bacteria that attack growing plants and insects and fungi that infest and infect products in storage. Weeds are also serious pests in the production of field crops. New methods for coping with pests are always being sought, and it is not surprising that high-frequency and microwave energy have been explored for these purposes.

Interest in controlling insects with high-frequency radio waves was recorded in the scientific literature more than 70 years ago. These reports, along with many since then on RF and microwave treatments for insect control, have been analyzed in previously published reviews [36, 39, 50, 49]. Most studies were related to control of stored-product insects and wood-infesting insects. Cereal grains and their products are among those most susceptible to insect infestation, particularly in the tropical and temperate regions of the world. Increasing concern about chemical pesticide residues in the 1950s and 1960s enhanced the interest in non-chemical methods for controlling such insects. Dielectric heating offered one possible alternative method.

Because the dielectric properties of insects and their host materials may differ, there is the possibility of selectively heating the insects to lethal temperatures through dielectric heating [74, 69, 36, 50]. The principle of selective dielectric heating is best explained by examining equations (18.2) and (18.3). Because the heating rate depends on the power dissipation P and the specific heat and specific gravity of the materials, those variables that influence P will be important in determining differential heating of components of a mixture. Thus, if a mixture of materials, such as insects and grain kernels, is subjected to dielectric heating by high-frequency or microwave electric fields, the relative power absorption will depend upon the relative values of the electric field intensity E and the dielectric loss factor ε'' for each of the materials in the mixture. The values of ε'' are characteristics of the materials and can be measured. The values for E in the different materials are more difficult to determine, because the field intensity distribution depends upon the dielectric constants ε' of the two materials and geometric factors [54]. Furthermore, both dielectric properties ε' and ε'' can vary with the frequency of the applied electric field.

Measured values for these properties of bulk samples of hard red winter wheat, *Triticum aestivum* L., and adult rice weevils, *Sitophilus oryzae* (L.), are shown in Fig. 18.3 [54]. Both materials exhibit broad dielectric relaxations between 1 MHz and 1 GHz, probably associated with bound water. It is interesting to note that the dielectric loss factor of the insects from 5 to 70 MHz is more than five times larger than that of the wheat. Based on these measurements, relative values for the electric field intensity E in the insect and in the grain were calculated according to a simple mathematical model, and power dissipation ratios for the insects and the grain were estimated. The most advantageous frequency range for selectively heating the insects was from about 10 to 100 MHz, where 3 to 3.5 times greater power dissipation could be expected in the insects than in the grain. Results of the analysis indicated that little selective heating of the insects could be expected at microwave frequencies (1 GHz or higher). Experimental treatment of wheat infested with adult rice weevils at frequencies of 39 MHz and 2.45 GHz confirmed this prediction [63]. Complete mortality of the insects was achieved by 39 MHz treatments at grain temperatures below 40°C, whereas exposures at 2.45 GHz had to produce temperatures in the grain above 80°C for comparable insect mortalities.

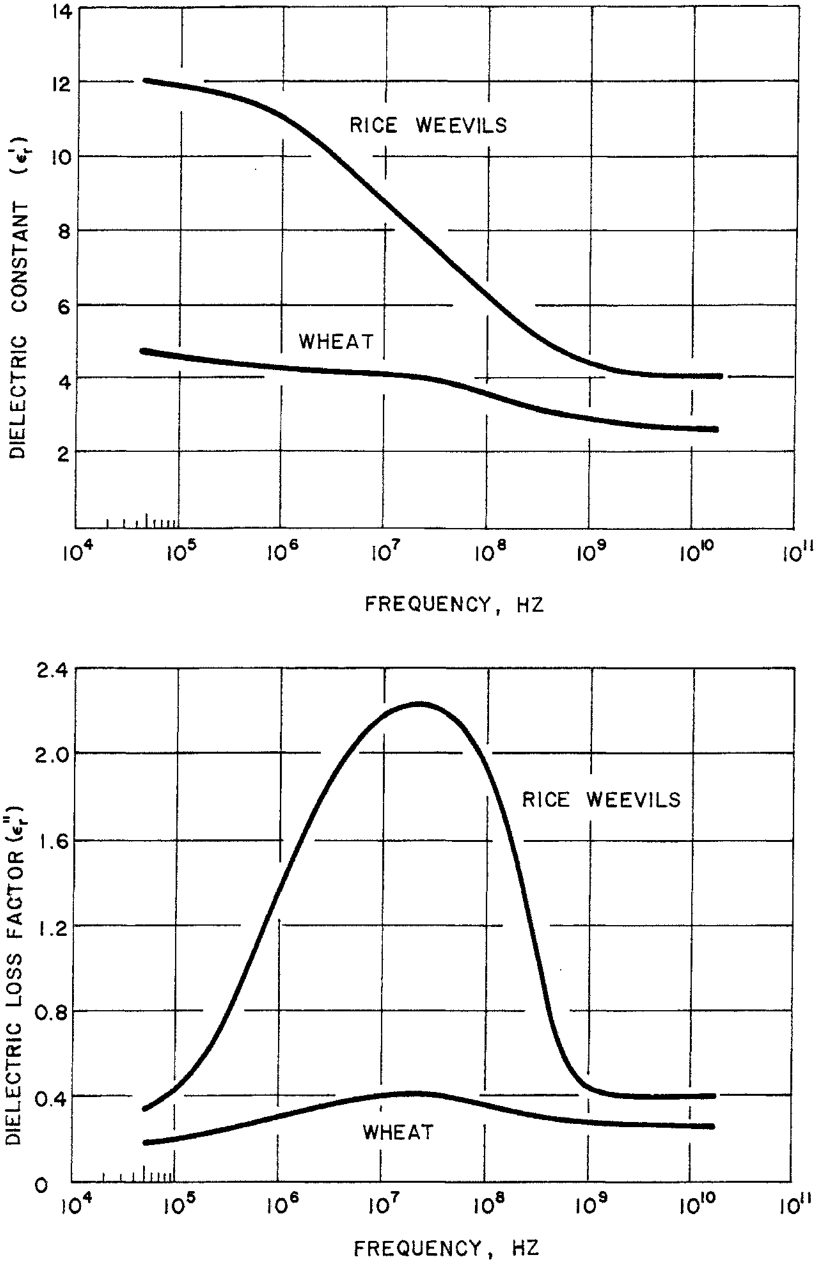

Fig. 18.3. Dielectric properties of bulk samples of hard red winter wheat (10.6% moisture content) and adult rice weevils (49% moisture content) [54].

Laboratory and pilot-scale tests in Switzerland of high-frequency insect control equipment operating at 12.6 MHz [7] confirmed earlier findings, in work at about 40 MHz [66], that final grain temperatures of about 60°C were necessary for control of the most resistant stored-grain insects.

Dielectric properties data on stored-grain insects were recently extended to higher frequencies and their dependence on temperature as well as frequency was determined [52, 53]. The new data provided no evidence for more efficient treatment of stored-grain insects at higher frequencies as suggested recently [18]. Some studies with pulsed 47.5 MHz electric fields and high-frequency and vacuum treatments with plasma formation have been reported [33], but conclusive work remains to be completed. No economically feasible RF or microwave treatments for controlling stored-grain insects have yet been demonstrated.

Use of microwave energy has also been considered for soil treatment to control weed seeds, insects, nematodes, and soil-borne micro-organisms [12, 88]. However, consideration of the dielectric properties of soils and the attenuation to be expected render the possibilities of success extremely remote as explained in a review and assessment of microwave energy for soil treatment to control pests [49].

Very recently, tests were made to determine how effective RF dielectric heating of alfalfa seed, inoculated with human pathogenic bacteria, might be for controlling such infections of seed used for production of edible sprouts [59]. Dielectric heating treatments at 39 MHz provided significant reductions in bacterial populations, but did not control the bacteria, *Salmonella, E. coli* O157:H7, and *Listeria monocytogenes*, without serious reductions in alfalfa seed viability. However, the treatments did provide significant increases in germination while at the same time providing moderate reduction in bacterial populations.

18.3.3 Seed Treatment

Studies reported more than 60 years ago on high frequency or RF treatment of seeds to improve germination are cited in a previous review [35]. Since then a large number of experiments concerning RF and microwave treatments of various kinds of seed have been described. Such studies on alfalfa, a species that has always responded favorably to RF and microwave dielectric heating treatments, were summarized and cited in an earlier review [41].

Results of experimental treatment of seed of more than 80 plant species with RF and microwave dielectric heating have been summarized [65]. Some small-seeded legumes, such as alfalfa, red clover, and arrowleaf clover, which often have naturally impermeable seed coats, responded consistently to dielectric heating treatments with marked increases in germination. Others, such as sweetclover, did not respond nearly so well. Benefits from RF treatment have been retained in alfalfa seed for up to 21 years in storage after treatment with no evidence of any detrimental effects. Several vegetable and ornamental species did not show any improvement as a result of RF seed treatment, but some, such as okra, garden peas, and garden beans, responded favorably. Germination of spinach was consistently accelerated [60].

In general, seeds of grasses, woody plants, and tree species did not respond very well. However, acceleration of germination was noted in some tests, and increases in germination were sometimes noted. Tests with field crops such as corn, cotton, and wheat showed acceleration of germination in some lots, as a result of treatment, but not in others. In those kinds of seed that did respond favorably, moisture content of the seed at the time of treatment influenced the degree of response. Generally, seeds of lower moisture content responded better to treatment than high-moisture seeds. The frequency of the fields used in seed treatment did not appear to be important. Instead, the final temperature of the seeds treated at any given moisture content seemed to be a good indicator of the degree of response. These findings still remain to be implemented for practical use.

18.3.4 Product Conditioning

Although microwave dielectric heating has found widespread application in the food industry and in microwave ovens in homes, it has found little use in the processing of other agricultural products. Microwave heating at 2.45 GHz was investigated for purposes of grain sorghum eversion for use in cattle feeding rations [6]. Kernel eversion was less than 50%, and very large equipment investments would have been required for practical-scale application.

RF and microwave heating have been studied for treatment of soybeans. Raw soybeans have a trypsin inhibitor that must be inactivated for efficient nutritional use by humans and monogastric farm animals. The enzyme, trypsin, is important in the digestion of protein; so trypsin inhibitor is normally inactivated by a moist heating process. Inactivation of the trypsin inhibitor can be accomplished by RF or microwave dielectric heating of soybeans with the natural moisture present in the soybeans [9, 44, 70]. Lipoxygenase, an enzyme associated with off-flavors, was also inactivated by the treatments, and peroxidase, a desirable enzyme, remained active in the treated soybeans. Protein digestibility and body weight gains of laboratory rats were improved by 2.45 GHz microwave heating of soybeans in other studies also [16, 11].

Tests have been conducted to determine whether dielectric heating treatments of pecans might prevent or delay development of rancidity during storage. Pecans must be stored at reduced temperatures to preserve their quality, and if holding periods are more than a few months, refrigerated storage at 0°C or lower temperatures is required. Limited studies showed that 43 MHz dielectric heating exposures of 1 to 2 min and steam treatments of 4 min were effective in stabilizing flavor quality during accelerated storage tests, but further studies would be needed to evaluate the processes before practical recommendations could be offered [61].

Product quality is not always improved by microwave heating. Adverse effects for milling purposes were noted in durum wheat after 2.45 GHz exposures [13].

18.4 Product Quality Sensing

When the dielectric properties of agricultural products can be well correlated with other physical or chemical characteristics that determine their suitability for particular uses or their value to consumers, there is the possibility of developing instruments for rapidly sensing these characteristics. The use of grain moisture meters for sensing the moisture content of grain is the best-known example of such applications. However, other possible applications have been considered, and some of these will be discussed.

18.4.1 Fruit and Vegetable Quality Sensing

Techniques for rapidly sensing quality factors of fresh fruit and vegetable produce are of great value in sorting such products for grading and marketing operations. Optical equipment for color sorting and surface defect detection has been in use for some time. Because high-frequency and microwave electric fields penetrate materials much better than visible, infrared, or ultraviolet radiation, they offer possibilities for detection of internal quality factors.

For these reasons, the dielectric properties of a few fruits and vegetables have been measured. In connection with quality sensing in fruits and vegetables, the dielectric properties of mature-green and full-ripe peaches at 2.45 GHz were examined to see whether these properties might be useful in distinguishing degree of maturity [43]. The same kind of measurements were taken on normal sweet potatoes and those that had a hard-core condition induced by chilling injury in storage [43]. Permittivity measurements at the single frequency of 2.45 GHz did not appear to offer promise for detecting either of these quality factors. Following permittivity characterization measurements for 23 kinds of common fresh fruits and vegetables over the frequency range from 200 MHz to 20 GHz at 23°C [56, 57], similar measurements were taken over a narrow range of peach maturity, and evidence for possible distinction of degree of maturity was obtained [58]. A permittivity-based maturity index was suggested, based on differences in both components of the permittivity, the dielectric constants at the low end of the frequency range, and the loss factors at 10 GHz near the higher end of this frequency range. More research and development are needed for determining the potential for practical use of the technique, including measurements at frequencies lower than 200 MHz, since the curves for the dielectric constants of the different maturities appeared to be diverging as they approached the lower end of the frequency range.

18.4.2 Grain and Seed Moisture Sensing

Moisture content is the most important characteristic of cereal grain affecting its suitability for harvesting, storage, transport, and processing. It is also an important factor affecting the price of grain. Therefore, moisture content must be determined whenever grain is traded. If moisture content is too high at the time of harvest, the grain kernels can be damaged in the mechanical harvesting process, leaving them more susceptible to infection by fungi. If they are stored at moisture contents too high for the prevailing environment, they can spoil because of the action of microorganisms, and the value is degraded or completely lost for human and animal consumption.

Reference methods for determining moisture in grain generally require oven drying at specified temperatures following prescribed laboratory procedures [86, 3], or chemical titration methods, which are also laboratory procedures. Therefore, these methods are too slow and tedious for practical use in the grain trade. Electrical measurement methods have been developed that depend on correlations between the electrical properties of the grain and moisture content [34, 42]. Electrical moisture meters for grain moisture determination have evolved over the past century [42, 48], and grain moisture meters today are predominantly those operating at frequencies in the range from 1 to 20 MHz that sense the dielectric properties, or permittivity, of the grain samples. These instruments, although troubled with inconsistency at moisture contents above 20% to 25% moisture content, perform reasonably well, and calibrations are maintained by the manufacturers for many different grain and seed commodities.

Moisture meters used in the trade require static samples, and corrections are made for variations in temperature and bulk density of the grain samples. Needs have long been recognized for moisture sensing instruments for applications with moving grain, and efforts have been devoted to developing RF dielectric-type moisture monitoring instruments. The need for moisture monitoring on combines as grain is harvested has spurred such development. Modern agriculture, involving "precision farming," which generally implies yield mapping with the application of global positioning systems and grain mass flow monitoring, requires reliable moisture monitoring also, because yield data need to be based on a specific moisture content. Fluctuation in bulk density, when grain is flowing, causes errors in moisture readings unless some compensation is provided for bulk density changes. Thus, moisture monitoring system design must provide some means for minimizing bulk density variation.

Research on sensing moisture content in grain by microwave measurements has indicated two important advantages for microwave frequencies. The inconsistency of moisture measurements by instruments operating in the HF range may be due, in part, to the influence of ionic conduction on the measured dielectric properties at high moisture levels. At microwave frequencies, the influence of ionic conduction is negligible, and better correlations between permittivity and moisture content can be expected. In addition, techniques for density-independent moisture sensing in granular materials have been reported for measurements at microwave frequencies [25, 26, 28, 29, 76, 77, 82]. Therefore, the principles for sensing moisture content in grain by microwave measurements are reviewed briefly and newer developments are summarized here.

18.4.3 General Principles

From a dielectrics viewpoint, a mass of grain can be characterized by the effective complex permittivity of the material, relative to free space, $\varepsilon = \varepsilon' - j\varepsilon''$, where ε' is the dielectric constant, and ε'' is the dielectric loss factor. For cereal grains, the permittivity is not only a function of the moisture content M, but also of the frequency f of the applied electric field, the temperature T of the grain, and the bulk density ρ of the grain. Thus, a plane wave traversing a layer of grain of thickness d will interact with the granular material as depicted in Fig. 18.4, where E_i represents the incident wave electric field, E_r is the reflected wave electric field, E_t is the electric field of the transmitted wave, Γ is the reflection coefficient, and τ is the transmission coefficient.

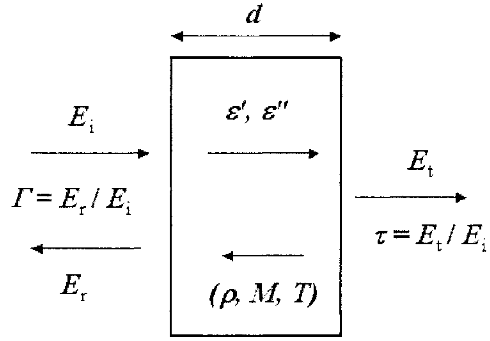

Fig. 18.4. Diagram of wave-dielectric material interaction

The components of the permittivity, ε' and ε'', can be obtained by measurement of the attenuation A and phase shift ϕ of the wave as it traverses the dielectric layer, because for a plane wave, when $\varepsilon'' << \varepsilon'$,

$$\varepsilon' = \left(\frac{\beta}{\beta_0}\right)^2 \tag{18.4}$$

$$\varepsilon'' = \frac{2\alpha\beta}{\beta_0} \tag{18.5}$$

where $\alpha = A/d$ is the attenuation constant, $\beta = \phi / d + \beta_0$ is the phase constant, and $\beta_0 = 2\pi / \lambda_0$ is the phase constant for free-space wavelength λ_0. The disturbance caused by any reflected waves within the grain layer can be made negligible by using a layer thickness that provides at least 10 dB of attenuation for waves traveling one way through the layer.

Measurements of attenuation and phase shift for grain have shown that both are relatively linear with moisture content [25]. Therefore the ratio of phase shift and attenuation, ϕ / A, has been considered for providing density-independent determinations for moisture content of grain [25]. For plane wave propagation through low-loss materials, this ratio can be expressed in terms of the permittivity of the grain as [23, 30]

$$\frac{\phi}{A} = \left(\frac{\varepsilon' - 1}{\varepsilon''}\right)\left(\frac{2\sqrt{\varepsilon'}}{\sqrt{\varepsilon'} + 1}\right) \tag{18.6}$$

The first term of the right-hand side of Eq. (18.6), $(\varepsilon' - 1)/\varepsilon''$, was considered earlier as a density-independent function in calibration equations for microwave measurement of moisture content of a number of particulate dielectrics [31, 32], because the second term had little significance for low-loss materials. However, work by Kress-Rogers and Kent [30] in food powders revealed that this term could be too important to neglect.

A newer density-independent function of the permittivity for moisture calibration in microwave measurements was reported by Trabelsi et al. [78]. This function was based on an observation of the complex-plane plot of ε'/ρ vs. ε''/ρ for a large set of measurements on hard red winter wheat at several frequencies, moisture contents, temperatures, and bulk densities. It was noted that, for permittivities determined from attenuation and phase measurements at a given frequency, all of the points fell along a straight line and that differences in either moisture content or temperature amounted to translations along that same line (Fig. 18.5). The lines for each frequency intersected the $\varepsilon''/\rho = 0$ axis at a common point, $\varepsilon'/\rho = k$, which represents the value of ε''/ρ for 0% moisture content or the value at very low temperatures. Any change in frequency amounted to a rotation of the straight line about that intersection point. Thus, for a given frequency, the equation of the line is expressed as

$$\varepsilon''/\rho = a_f(\varepsilon'/\rho - k) \tag{18.7}$$

where a_f is the slope at a given frequency. It was determined that the slope varied linearly with frequency. Solving Eq. (18.7) for ρ, we have

$$\rho = \frac{a_f \varepsilon' - \varepsilon''}{a_f k} \tag{18.8}$$

For a given frequency, a_f is a constant, and for a given material, k is a constant. Thus, the bulk density is provided by Eq. (18.8) in terms of the permittivity alone, without regard for temperature or moisture content. Considering that $\tan\delta = \varepsilon''/\varepsilon'$, where δ is the loss angle of the dielectric, expresses the distribution between dissipated and stored energy in a dielectric, and that $\tan\delta$ varies with bulk density, it was divided by bulk density.

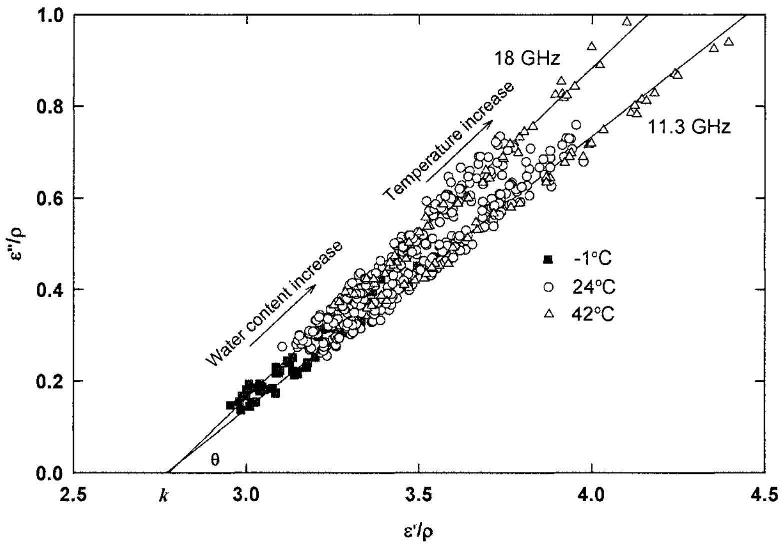

Fig. 18.5. Complex-plane plot of the dielectric constant and loss factor, divided by bulk density, for hard red winter wheat of various moisture contents and bulk densities at indicated temperatures for two frequencies, 11.3 and 18.0 GHz [78].

Using Eq. (18.8) for ρ, we can write

$$\frac{\tan\delta}{\rho} = ka_f\left(\frac{\varepsilon''}{\varepsilon'\left(a_f\varepsilon' - \varepsilon''\right)}\right) \tag{18.9}$$

For a given frequency and particular kind of material, ka_f is a constant, and a new density-independent moisture calibration function can be defined as follows:

$$\psi = \sqrt{\frac{\varepsilon''}{\varepsilon'\left(a_f\varepsilon' - \varepsilon''\right)}} \tag{18.10}$$

The quadratic relationship between the calibration function ψ and the permittivity function of Eq. (18.9) for changes in moisture content was determined empirically [78].

The new calibration function has been studied for a large set of measurements on hard red winter wheat over practical ranges of moisture content, bulk density, and temperature. Figure 18.6 shows the variation of ψ with moisture content M and temperature T at one frequency, 14.2 GHz. Because ψ is linear with both M and T, all of the data points fall on a plane for which the equation can be obtained by regression analysis, providing the values for the constants, a, b and c in the following equation:

$$\psi = aM + bT + c \tag{18.11}$$

The resulting equation for moisture content,

$$M = (\psi - bT - c)/a \tag{18.12}$$

is then given in terms of the density-independent calibration function ψ, which, at any given frequency, depends only on the grain permittivity, as shown in Eq. (18.10). The dielectric constant and loss factor can be determined by any suitable microwave measurement.

Further research with this new density-independent moisture calibration function has shown that very similar values of regression constants were obtained for kinds of grain as different as wheat and corn [79]. In another comparison, the same constants performed very well for wheat, oats, and soybeans, which have very different characteristics with respect to kernel shape, size, and composition [84]. These findings support the idea of a universal calibration for grain and seed.

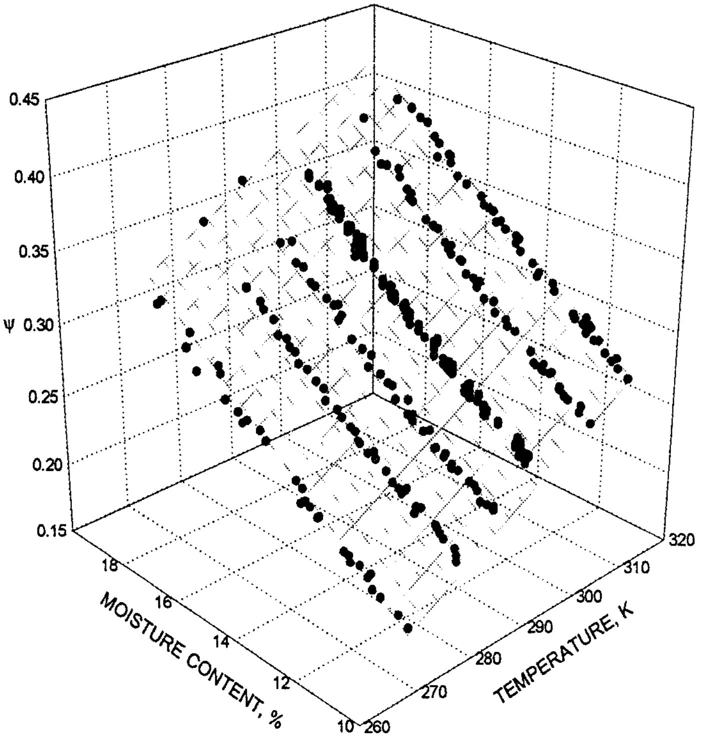

Fig. 18.6. Moisture and temperature dependence of density-independent function ψ at 14.2 GHz for hard red winter wheat [79]

The rapid, non-destructive, reliable sensing of moisture content in cereal grains and other agricultural crops is essential in modern agriculture for prevention of losses and improvements in efficiency of production of these sources of food. Measurement or sensing of the relative complex permittivity, or dielectric properties, at microwave frequencies offers advantages that include density-independent sensing of moisture content and the reduction of variations that arise from ionic conductivity of high moisture grain samples at lower radio frequencies. These advantages, along with the promise for a universal moisture calibration, should encourage the development of microwave measurement systems for on-line moisture sensing for cereal grains and granular materials in other industries as well as in agriculture.

18.5 Potential for Further Applications

Predicting further applications for dielectric properties information entails the risk of being mistaken, but in view of past applications, some observations can be offered concerning likely developments.

The need for rapid quality determination for many agricultural products will inspire further research on correlations between the quality factors of products and their dielectric properties. No doubt there will be quality factors other than moisture content that can be sensed through these correlations, particularly when broad frequency band data are considered. The availability of broadband permittivity measurement techniques will permit relatively efficient collection of such data for developing useful correlations. When such potentially useful correlations are verified, the engineering challenges of designing equipment to utilize the new information must be met for economically feasible applications.

With respect to grain and seed moisture sensing, and the sensing of bulk density also where it may be of value, the advantages outlined for microwave frequencies should encourage the development of instruments operating at these frequencies. Because of the advances in the development of communications equipment, and the scale of these applications, the costs of many components for such circuits have become very reasonable. This should improve the chances for developing economically practical instruments for sensing the dielectric properties of interest in agricultural products. The development of applicable microstrip antennas, which can be produced at low cost, is another factor that would contribute substantially to the development of microwave moisture meters and other instruments that can utilize the dielectric properties for rapid assessment of quality in agricultural products.

Of course, further research may open entirely new applications, where the dielectric properties of products will provide the means for sensing internal quality, conditions, or other information of practical interest.

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