AN OVERVIEW OF ELECTROMAGNETIC RADIATION IN GRAIN CROPS

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ABSTRACT

Electromagnetic radiation is becoming an effective tool in diverse technologies and scientific fields. A comprehensive knowledge of this electromagnetic radiation with grain crops is the promising potential for effective exploitation of electromagnetic fields. However, its role in controlling the bulk of grain in storage still is not vigorously investigated. This paper reviews the application of electromagnetic fields for cereal crops management providing a brief introduction on the basic laws of electromagnetic radiation and knowledge of electromagnetic fields with wheat grains. It also discusses application of electromagnetic heating and sensing in cereal grain processing operations such drying, disinfestations, and storage as well as the factors that affect the dielectric properties of the cereal grains in the context of samples and process parameters. The study also provides the recommendations for future research to achieve the accurate measurements of moisture content and temperature for proper wheat grains storage.

KEYWORDS

Dielectric Properties, Wheat grains, Moisture Content, Temperature

1. INTRODUCTION

Electromagnetic energy is an important factor in agricultural products processing. When this energy moves in the form of electromagnetic waves away from the source is called electromagnetic radiation. Electromagnetic radiation is categorized according to frequency waves such as radio waves, microwave, infrared, visible light, ultraviolet radiation, X-rays, and gamma rays. It is usually applied to food products for the purpose of keeping their quality. In developing countries, farmers spread their crop grains to dry under the sun, which often requires longer durations for the product to attain safe moisture level. The grains are usually spread out on the ground, or rock surfaces, or on nylons till the products are dry. Farmers sometimes stack the food products, bringing grains under cover and drying them over the fire [1, 2]. Another method is to pass the air through the grain mass in storage with the support of natural air, fans, and suction methods. After that, the moisture is absorbed and carried away from the grain mass [3, 4]. Modern technology for drying grains involves applying electromagnetic heating. Once it is applied to food products, the thermal heat energy is transferred in the form of electromagnetic waves and absorbed by the food products. Temperature distribution inside food products heated with microwave is determined by both thermal properties of the products and the distribution of the absorbed microwave energy [5-8]. For several years, electromagnetic field has been primarily applied in agricultural products processing with little practical application in monitoring the grain bulk from moisture content and temperature. The frequency of the electromagnetic field is used to measure just surface layers and not the whole product [9]. Grain temperature and moisture content are considered to be principal factors for safe storage of grains, if they are well controlled [10, 11]. However, in the past few years, significant research efforts have been made in the vicinity of sensing moisture and temperature of grain samples in laboratories using electromagnetic principles. Therefore, this article explores the existing technologies to provide insights for the relationship between dielectric properties and large mass of grains in storage so as to sense moisture content and temperature from the grain bulk. The study also covers other applications such as drying, disinfestations, and pasteurization of cereal grains.

2. ELECTROMAGNETIC RADIATION BASIC LAWS

Electromagnetic radiation is described by the equations with five components such as H, B, E, D, ρ and J. H and B denote magnetic field in A/m and magnetic flux density in Vs/m^2 respectively. E and D denote electric field in V/m and electric displacement in As/m^2 respectively. On the other hand, J and ρ denote current density in A/m^2 charge density in As/m^3 of the medium. The equations with these components are the Maxwell's equations which govern the behaviour of the electromagnetic fields. In dielectric medium, there are neither free (free currents) nor bound charge density. There is also no magnetization current density. However, there is a polarization current due to time variation of the induced dipole moment per unit volume. The polarization current [12, 13] is given as:

$$\mathbf{j} = \frac{\partial \mathbf{P}}{\partial t} \tag{1}$$

In these media, the conductivity of the medium is zero (σ = 0) and there is no charge in it (ρ = 0). The reflective index n of the medium is expressed as:

$$\boldsymbol{n} = \sqrt{\boldsymbol{\varepsilon}} \tag{2}$$

Electromagnetic radiation is described by Maxwell's equations with corresponding boundary conditions. These equations are the same as those in free space as expressed by the laws below [14]:

Faraday's law in point form: $$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{H}}{\partial t} \tag{3}$$

Ampere's law in point form: $$\nabla \times \mathbf{H} = \boldsymbol{J} + \frac{\partial \mathbf{D}}{\partial t} \tag{4}$$

Gauss' law for the electric field: $$\nabla \cdot \mathbf{D} = \mathbf{0} \tag{5}$$

Gauss' law for the magnetic field: $$\nabla \cdot \mathbf{B} = \mathbf{0} \tag{6}$$

3. ELECTROMAGNETIC FIELDS WITH CEREAL CROPS

When electromagnetic wave is incident on a matter with different electromagnetic properties from the matter interface, partial reflection occurs at the boundary between the two media. Some fraction of the incident wave may be transmitted and the rest may be absorbed as shown in add

Figure 1. If the impedances of the two media are almost equal, most of energy is transmitted and the reflected signal is relatively small. Conversely, if the impedances differ greatly, the transmitted signal is small and the reflected one is relatively large. This particular type of interaction depends on the energy of the wave and the structure of the matter. The interaction with electromagnetic energy is always influenced by the intrinsic properties of the matter (dielectric properties) [14-16]. The dielectric properties (dielectric constant ε' and the dielectric loss factor ε") of the relative complex permittivity [11] are the main parameters that provide information about how materials interact with electromagnetic energy [17]. The relative complex permittivity of a material is expressed as:

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{7}$$

Where, ε' is the dielectric constant that describes the ability of a material to store energy, ε" is a dielectric loss factor that describes the ability of a material to dissipate energy. Electromagnetic wave diminishes by 1/e after passing a certain distance (penetration depth, dp) through a material [18]:

$$d_p = \frac{c}{2\pi f \sqrt{2\varepsilon'\left[1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2 - 1\right]}} \tag{8}$$

Whereby, c is the speed of light in free space, and e is equal to 2.7183

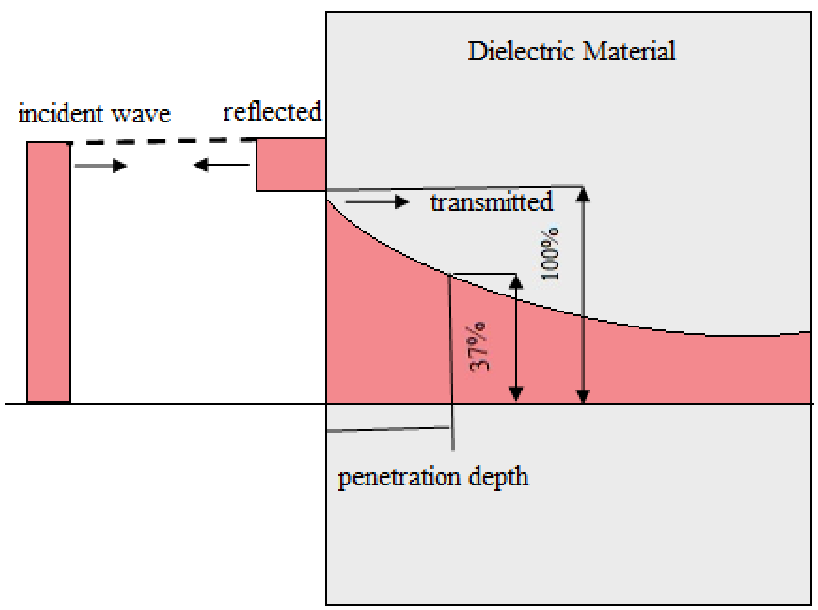

Figure 1. When electromagnetic strikes with high loss factor

[19] Biological materials such as living organisms and agricultural products are dielectrics though they conduct electric currents to some degree. The electrical nature of these materials is described by their dielectric properties. These properties influence the distribution of electromagnetic fields and currents, and determine the behaviour of the materials in electric fields [20]. A bulk of grains represents a disperse system of dielectric medium formed by dispersive particles and air spaces between them. Every particle (grain) has the porous structure and also can be considered as a complex disperse system. It is formed by organic substance of inhomogeneous composition and

density, with air micro capillaries in it and micro particles of absorbed water [21]. The mathematical formulation developed by Debye is used to describe the electrical properties of materials. It is given as [22, 23]:

$$\varepsilon' = \varepsilon_\infty + \frac{\varepsilon_S - \varepsilon_\infty}{1+\omega^2\tau^2} \quad (9)$$

$$\varepsilon'' = \frac{(\varepsilon_S - \varepsilon_\infty)\omega\tau}{1+\omega^2\tau^2} \quad (10)$$

Whereby ε_∞ is the dielectric constant at high frequency where orientation does not contribute to polarization, ε_s is the static dielectric constant at zero frequency, τ is the relaxation time in seconds where dipoles lapse to random orientation when the electric field is removed, and ω is the angular frequency, since the grain bulk is considered as dispersive medium with a mixture of grains and air. Various dielectric mixture equations are used to estimate the dielectric properties of an air particle mixture [24]:

a. Landau & Lifshitz, Looyenga equation

$$(\varepsilon)^{1/3} = V_1(\varepsilon_1)^{1/3} - V_2(\varepsilon_2)^{1/3} \quad (11)$$

b. Complex Refractive Index mixture equation

$$(\varepsilon)^{1/2} = V_1(\varepsilon_1)^{1/2} - V_2(\varepsilon_2)^{1/2} \quad (12)$$

Whereby, ε is the complex permittivity of the mixture medium, $\varepsilon 1$ is the complex permittivity of air that is 1-j0, $\varepsilon 2$ is the complex permittivity of the particle medium, and v1 and v2 are the volume fractions of the mixture of air and the bulk particle medium respectively. ρ is the air particle mixture density and $\rho 2$ is the particle material density. The total volume fraction is expressed as [24]:

$$v_1 + v_2 = 1 \quad (13)$$

$$v_2 = \frac{\rho}{\rho_2} \quad (14)$$

4. ELECTRICAL PROPERTIES OF GRAIN CROPS

Dielectric properties of grains are affected by various factors such as moisture content, temperature, bulk density, frequency, and storage time. In cereal crops, the amount of water in the material is generally a dominant factor [22, 25, 26].

4.1. Temperature Effect

The effect of temperature on the dielectric properties of cereal grains has been studied by a number of researchers. The study [27] presented the influence of temperature on dielectric properties of loose fill buckwheat seed samples in the range of 1 to 1000 kHz, temperatures from 5°C to 40°C and moisture content from 11.1% to 17.1% using a coaxial cylindrical capacitor. The findings showed that dielectric constant and dielectric loss factor both increased with increasing in temperature as shown in Figures 2 and 3. Moreover, the study [28] reported temperature dependence of dielectric permittivity of grains at radio frequencies. The dielectric permittivity of bulk wheat samples at various temperatures was measured. The result indicated that dielectric constant of the wheat increased almost linearly with temperature, and varied between 3.82 and 5.95. Also, the loss factor increased nonlinearly with temperature with values between 0.07 and 0.93.

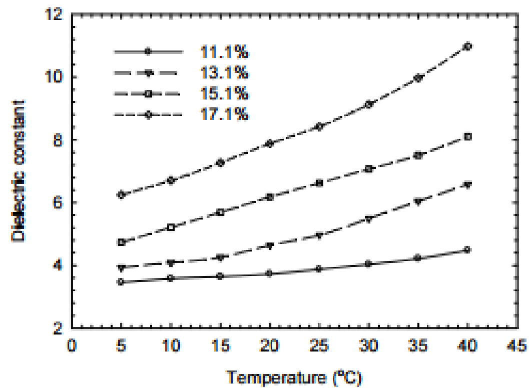

Figure 1 Variation of dielectric constant of loose fill buckwheat with temperature at different moisture content

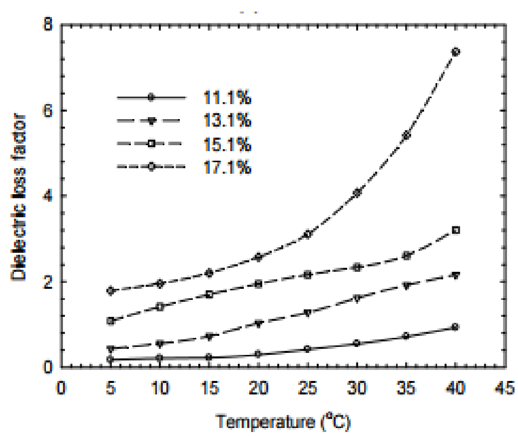

Figure 2. Variation of loss factor of loose fill buckwheat with temperature at different moisture content

4.2. Frequency Effect

The dielectric properties of most materials such as cereal grains vary significantly with the frequency of the electromagnetic fields. The polarization is the key factor that contributes to the frequency dependence of the dielectric [22] as shown in Figure 4 and 5. The study taken at the range of 10 MHz to 1.8 GHz reported that the dielectric properties of hard red winter wheat decreased consistently with increasing frequency [29]. The dielectric constant of grains [30] increases with increasing frequency while the loss factor may either increase or decrease with increasing frequency as shown in Table 1. It was also reported in [31] that dielectric properties of cereal grains such as wheat, corn, barley, oats, and grain sorghum were measured at 23°C. The technique used was a free-space transmission at the range of 5 to 15 GHz. It was found that the dielectric constants of all grains decreased with increasing frequency and increased with increasing moisture content. Loss factors varied slightly with increasing frequency, remaining almost constant for barley and oats, while decreasing slightly with increasing frequency for wheat and grain sorghum, and increasing slightly with increasing frequency for corn.

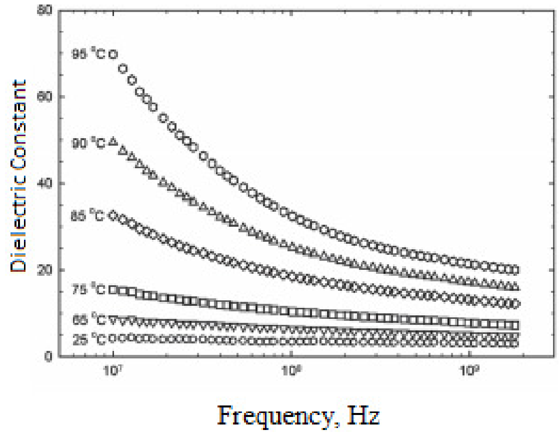

Figure 3. Dielectric constant of hard red winter wheat as the function of frequency at different temperature

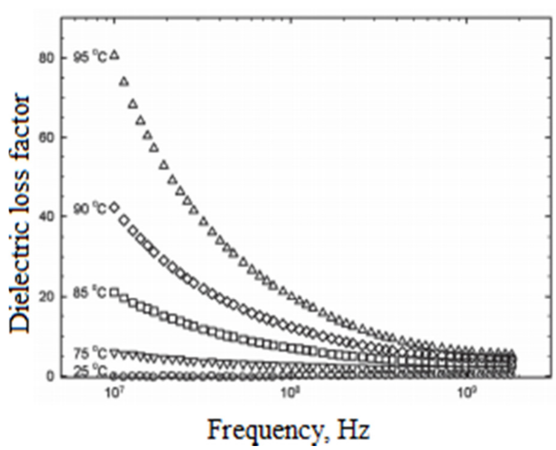

Figure 4. Loss factor of hard red winter wheat as the function of frequency at different temperature

4.3. Moisture Content Effect

Various studies reported that moisture content has significant effects on most properties of agricultural products. One of these properties which are highly affected by moisture content is the dielectric constant of grains and seeds. High moisture level causes the total polarization of the grains and seeds to increase [32-34]. In the study [33], the dielectric constant of wheat and millet was investigated as the function of moisture content and frequency. Polynomial and homographic regression was used to analyze the relationship of dielectric constant and moisture content. The findings showed that the dielectric constant increased homographically with the increase of moisture content as demonstrated in Figure 4. Table 1 shows that the moisture content [30] influences the dielectric properties of grains at any frequency. The dielectric loss factor is found to be less predictable than the dielectric constant and may either increase or decrease with moisture content, depending upon the particular range of moisture content. The other study [34] presented the determination of dielectric properties of corn seeds in the ranges of 9.71–21.51% wet basis (w.b.) for moisture content, 772.5–902.2 kg/m^3 for bulk density and the frequency range of 1–100 MHz using a coaxial capacitor sample holder. Effects of the parameters such as moisture content, bulk density, and frequency on the dielectric properties were investigated. It was observed that, the moisture content was the most significant factor affecting the dielectric properties of corn seeds as demonstrated in Figure 6.

Table 1. Dielectric properties of grains at different moisture contents and frequencies [30]

Gain	**MC (%)**	**Frequency (GHz)**					
		10		40		1	
		ε'	ε"	ε'	ε"	ε'	ε"
Barley, spring	12.9	32	0.25	3	0.03		
Rye, winter	12.7			4	0.52		
Oats, spring	10.7	2.8	0.2			2.2	0.18
Sorghum, spring	11.4	4.2	0.38			2.9	0.29
Wheat	12.5					2.89	0.35
Oats	10.7					2.12	0.16
Sorghum	11.4					2.81	0.34

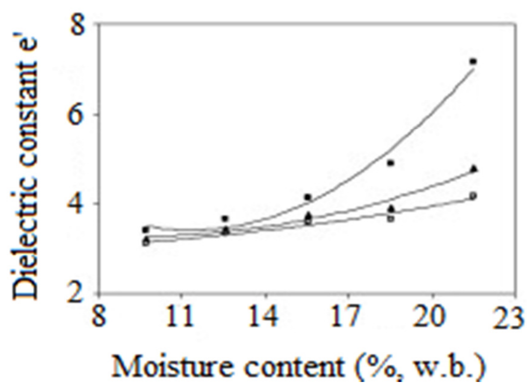

Figure 5. Variation of dielectric constant of corn with moisture content

4.4. Bulk Density Effect

The density (mass per unit volume) has an effect on the dielectric properties because these properties depend on the amount of mass interacting with the electromagnetic fields. The size of particles in the mixture when gets much smaller than the wavelength of the waves, the effective permittivity depends only on the shape of the particles and is independent of their size [22, 35]. The granular density of grain seed is reported to covers a range from 0.5-0.85 cm^3, where 1 cm^3 contains about 30-35 seeds [36]. The study [25] reported the bulk density of grain sorghum hybrid (BRS 308, BRS 310, BRS 655and CMSXS 769) that was experimentally determined with respect to the dielectric properties and moisture content in the range of frequency from 75 – 5 MHz using a chondrometer. The bulk density was in the range of 575 - 819 kg/m^3 and moisture content from 7 – 23%. The experimental results proved that the bulk density decreased with increasing moisture content for cereal grains. Furthermore, it was also presented that the dielectric constant and loss factor of wheat straw depended on the bulk density, temperature, and moisture content and the frequency in the range of 1 to 1000 kHz. The bulk density was in the range of 47.3 - 108.1 kg/m^3, temperature in the range of 5°C - 40°C and moisture content in the range of 10% - 20%. Both dielectric constant and loss factor increased with an increase in bulk density, temperature, and moisture content [35].

4.5. Storage Time Effect

The storage time can change the dielectric properties of grains. If grains are placed in a humid place they can easily absorb moisture. Also, when they are kept in a dry place they can lose moisture. Both dielectric constant and dielectric loss decrease with an increase in storage time due to the reduction of moisture content. During this time, Ph increases and the electrical conductivity increases with an increase temperature [37]. The age of each seed sample (wheat, barley, maize and common bean) was taken as the number of years that had elapsed since their harvest. Based on the germination of the five accessions per reproduction cycle, analysis was performed. [38] reported that germination of each decreased over storage time.

5. ELECTROMAGNETIC HEATING EFFECTS ON CEREAL CROPS

The effects of radio frequency and microwave energy are mainly thermal in nature. Most agricultural products that are considered as dielectric material can store electric energy and convert electric energy into heat [39]. The study [40] presented microwave frequency use in the analysis of dielectric properties of barley, corn (white and yellow), sorghum, and wheat for heating purpose. Properties were determined at 915, 2450 and 5800 MHz with a free space transmission method in the cereals at 20, 30, 40, 50, and 60 °C. The results showed that the penetration depth decreased with increasing frequency for all the samples, and increased with increasing temperature at 915 MHz, except for barley. The results also showed promise for further microwave heating applications for the studies on cereal. The other study [41] presented the radio frequency of 27 MHz in a pilot-scale with 6 kW. The technique was used to study the heating uniformity in corn samples with five moisture contents. It also used three plastic material containers, and developed a treatment protocol for a corn sample with the moisture content of 15.0% w.b. It was found that only 7.5 min was needed to raise the central temperature of 3.0 kg corn samples from 25 °C to 70 °C using the RF energy, but 749 min were needed for samples to reach 68.6 °C using hot air at 70 °C. Corn quality was not affected by the RF treatments even after the accelerated storage. However, the effective and better environment for pasteurizing corns must be provided. Moreover, the feasibility of radio frequency selective heating as a disinfestation technique was investigated at 27.12 MHz. The effectiveness of technique was assessed using power dissipation factors and the rate of increase of temperature in the insect bodies and wheat kernels. The results had a significant effect on insect to wheat power absorption factor which varied between 5 and 40. The relative rate of increase of temperature for insect to wheat was directly related to power absorption factor, but inversely related to the product of insect/grain specific heat and density [42].

6. ELECTROMAGNETIC SENSING EFFECTS ON CEREAL CROPS

The study [43] presented the development of a low-cost microwave sensor for sensing of moisture content in granular and particulate materials. It operates at a single frequency of 5.8 GHz in free space transmission for moisture determination. It was found that moisture content in wheat and soybeans can be determined in either material from a single moisture calibration equation. However, the simplicity of use, low price, and level of accuracy of the developed sensor can be useful integration of microwave sensing technology in industries for granular and particulate materials such as food, and agriculture [43]. In additional, the analysis and optimal design of a multi-layered microstrip sensor for measuring moisture content of rice grain were presented. The sensor operated at 9 GHz and was suitable for a broad range of moisture contents

(MC) ranging from 10% to 30% (wet basis). This study investigated the optimal thickness of the protective layer for suitable sensitivity, the thickness of grain medium which can be considered as semi-infinite thickness, the effect of kernel density and loading method. It was found that, the attenuation of the signal at various moisture contents agree reasonably with the theoretical prediction. However, for better accuracy, the compactness of grain medium should be observed. [44].

Nonetheless, most applications were conducted in laboratories not for commercial or industry use [19]. Also, the maximum penetration depth by microwave frequency seemed to be lower than that of radio frequency due to its short wavelength. RF treatment has deeper penetration than MW treatment. This penetration depth determines the size and shape of food products. RF can be used to treat the large bulk of material than Microwave. But, there is no limitation on the size and shape of products for microwave application, while RF needs to treat material with regular and simple shape. Microwave treatment also is so cheap [18]. Moreover, when the size of particle is much smaller than the wavelength of the wave, the effective permittivity depends only on the shape of the particles and is independent of their size.

7. CONCLUSION

From the literature review, many studies conducted over the years have shown that the exposure on the use of electromagnetic radiation for food security is very important. Differences have been renowned in the issue of wave penetration depth through the bulk of grains between the radio and microwave frequencies. In general, the microwave penetration depth is not as good as radio frequency depth, but it does not consider the size and shape of grain products for radiation as in RF. This makes microwve better for almost all types of grain product processing. The use of electromagnetic radiation for moisture and temperature control in grains storage has several advantages as follows:

- It is non destructive method that never affects the physical properties of wheat grains.
- It can characterize the dielectric properties of wheat grain for the whole storage due to the intruders (variation of moisture content and temperature) with respect to the operating frequency.
- The method can provide a safe ground for wheat grains storage against mycotoxin, insects, and mold activities that cause the grain losses and degradation of grain quality.

Since, the moisture content and temperature control of large quantity of grains (wheat) has not been much explored, extra investigations regarding electromagnetic radiation are still required for the successful applications of the wheat storage in future. Moisture and temperature controlled processes with respect to dielectric properties have to be considered for large quantity of wheat grains in storage. The spatial and temporal measurement method for wheat water and temperature monitoring must also be considered so that the safe grain storage condition is successfully achieved with regard to radiation depth through the wheat medium.

REFERENCES

[1] S. Bankole and A. Adebanjo, (2004) "Mycotoxins in food in West Africa: current situation and possibilities of controlling it," African Journal of Biotechnology, vol. 2, pp. 254-263.
[2] P.W Wambugu, P.W Mathenge, E.O Auma & HA van Rheenen, (2009) "Efficacy of traditional maize (Zea mays L.) seed storage methods in western Kenya," African Journal of Food, Agriculture, Nutrition and Development, vol. 9.
[3] K Pierson, B Macdonald & J Penne., (2009) "Grain drying aeration system," ed: Google Patents.
[4] O. Khatchatourian & F. De Oliveira, "Mathematical modelling of airflow and thermal state in large aerated grain storage," Biosystems Engineering, vol. 95, pp. 159-169, 2006.
[5] A. K. Datta, (2001) Handbook of microwave technology for food application: CRC Press, 2001.
[6] M. S. Rahman, (2007) Handbook of food preservation: CRC press.
[7] H. Ramaswamy and J. Tang, (2008) "Microwave and radio frequency heating," Food Science and Technology International, vol. 14, pp. 423-427, 2008.
[8] M. Oliveira and A. Franca, (2012) "Microwave heating of foodstuffs," Journal of Food Engineering, vol. 53, pp. 347-359, .
[9] U. Kaatze and C. Hübner, (2010) "Electromagnetic techniques for moisture content determination of materials," Measurement Science and Technology, vol. 21, p. 082001.
[10] MS Uddin, PR Armstrong, N Zhang, (2006) "Accuracy of grain moisture content prediction using temperature and relative humidity sensors," Applied engineering in agriculture, vol. 22, pp. 267-273, 2006.
[11] S. Nelson, (2008) "Dielectric properties of agricultural products and some applications," Research in Agricultural Engineering, vol. 54, pp. 104-112.
[12] A. Kirsch and F. Hettlich, (2014) The Mathematical Theory of Time-harmonic Maxwell's Equations: Expansion-, Integral-, and Variational Methods vol. 190: Springer.
[13] C. Müller, (2013) Foundations of the mathematical theory of electromagnetic waves vol. 155: Springer Science & Business Media.
[14] V Komarov, S Wang & J Tang., (2005) "Permittivity and measurements," Encyclopedia of RF and microwave engineering.
[15] S Govindarajan, DS Jayas, NDG Whit & J Paliwal, (2005) "Dielectric properties measurement of bulk wheat samples using reflection and transmission techniques, CSAE," in SCGR 2005 Meeting.
[16] J. C. Lin and S. M. Michaelson, (2013) Biological effects and health implications of radiofrequency radiation: Springer Science & Business Media.
[17] N Bhargava, R Jain, I Joshi & KS Sharma, (2014) "Investigation of Dielectric Properties of Some Varieties of Wheat and their Correlation with Food Nutrients," vol. 3, pp. 392-400.
[18] B Awuah, HS Ramaswamy & J Tang, (2014) Radio-Frequency heating in food processing: Principles and applications: CRC Press.
[19] L Hou, JA Johnson & S Wang., (2016) "Radio frequency heating for postharvest control of pests in agricultural products: A review," Postharvest Biology and Technology, vol. 113, pp. 106-118.
[20] S. O. Nelson, (2010) "Fundamentals of dielectric properties measurements and agricultural applications," J. Microw. Power Electromagn. Energy, vol. 44, pp. 98-113.
[21] V. M. Serdyuk, (2008) "Dielectric study of bound water in grain at radio and microwave frequencies," Progress In Electromagnetics Research, vol. 84, pp. 379-406.
[22] S. O. Nelson and S. Trabelsi, (2012) "Factors influencing the dielectric properties of agricultural and food products," Journal of Microwave Power and Electromagnetic Energy, vol. 46, pp. 93-107.
[23] CL Jones, ML Stone & NO Maness, (2006) "Plant biomass estimation using dielectric properties," in 2006 ASAE Annual Meeting, p. 1.
[24] B Alfaifi, J Tang, Y Jiao, S Wang & B Rasco, (2014) "Radio frequency disinfestation treatments for dried fruit: Model development and validation," Journal of Food Engineering, vol. 120, pp. 268-276.
[25] EE Moura, PA Berbert, EF Souza & RF Garcia, (2016) "Frequency, moisture content, bulk density and hybrid effects on grain sorghum dielectric properties," Agricultural Engineering International: CIGR Journal, vol. 18, pp. 236-255.
[26] Y Wang, L Zhang, M Gao, J Tang & S Wang., (2013) "Temperature-and moisture-dependent dielectric properties of macadamia nut kernels," Food and Bioprocess Technology, vol. 6, pp. 2165-2176.
[27] X Zhu, W Guo & S Wang., (2013) "Sensing moisture content of buckwheat seed from dielectric properties," Transactions of the ASABE, vol. 56, pp. 1855-1862.

[28] B. Shrestha and O. Baik, (2015) "Dielectric behaviour of whole-grain wheat with temperature at 27.12 MHZ: A novel use of a liquid dielectric test fixture for grains," International Journal of Food Properties, vol. 18, pp. 100-112.

[29] S. O. Nelson and S. Trabelsi, (2009) "Influence of water content on RF and microwave dielectric behavior of foods," J. Microw. Power Electromagn. Energy, vol. 43, pp. 13-23.

[30] N. Ismail and N. M. Asri, "Optimisation of microwave system for rice treatment," Universiti Tun Hussein Onn Malaysia, 2014.

[31] S. Trabelsi and S. Nelson, (2012) "Microwave dielectric properties of cereal grains," Transactions of the ASABE, vol. 55, pp. 1989-1996.

[32] R Thakur, S Chatterji & A Kumar., "Studies on electrical properties of wheat as a function of moisture content," Quality Assurance and Safety of Crops & Foods, vol. 3, pp. 198-204, 2011.

[33] M. Soltani and R. Alimardani, (2013) "Investigation of the Relationship between Moisture Content and Dielectric Constant of Wheat and Millet," Journal of Scientific & Industrial Research, vol. 72, pp. 415-418.

[34] K. Sacilik and A. Colak, (2010) "Determination of dielectric properties of corn seeds from 1 to 100 MHz," Powder Technology, vol. 203, pp. 365-370.

[35] W Guo, J Yang, X Zhu & S Wang., (2013) "Frequency, moisture, temperature, and density-dependent dielectric properties of wheat straw," Transactions of the ASABE, vol. 56, pp. 1069-1075.

[36] AV Castrejón & MVR González, (2015) "Study of dielectric parameters and the internal electric field prediction in an individual wheat grain particle," in Electrical Engineering, Computing Science and Automatic Control (CCE), 2015 12th International Conference on, pp. 1-5.

[37] M. I. Ponomaryova, (2011) "Model of Electromagnetic Interaction With Granular Product and Insects," .

[38] M. Nagel and A. Börner, (2010) "The longevity of crop seeds stored under ambient conditions," Seed Science Research, vol. 20, pp. 1-12.

[39] I Das, G Kumar & NG Shah, (2013) "Microwave heating as an alternative quarantine method for disinfestation of stored food grains," International Journal of Food Science, vol. 2013.

[40] R Torrealba-Meléndez & ME Sosa-Morales, (2015) "Dielectric properties of cereals at frequencies useful for processes with microwave heating," Journal of Food Science and Technology, vol. 52, pp. 8403-8409.

[41] A Zheng, B Zhang, L Zhou & S Wang, (2016) "Application of radio frequency pasteurization to corn (Zea mays L.): Heating uniformity improvement and quality stability evaluation," Journal of Stored Products Research, vol. 68, pp. 63-72.

[42] B. Shrestha and O.-D. Baik, (2013) "Radio frequency selective heating of stored-grain insects at 27.12 MHz: a feasibility study," Biosystems Engineering, vol. 114, pp. 195-204.

[43] S Trabelsi, SO Nelson & M Lewis, (2008) "Microwave moisture sensor for grain and seed," Biological Engineering Transactions, vol. 1, pp. 195-202.

[44] F Jafari, K Khalid, WMDW Yusoff & J Hassan., (2010) "The analysis and design of multi-layer microstrip moisture sensor for rice grain," Biosystems Engineering, vol. 106, pp. 324-331.

[45] D. S. Jayas, (2007) "Sensors for Grain Storage," in 2007 ASAE Annual Meeting, p. 1.

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