Density-independent algorithm for sensing moisture content of sawdust based on reflection measurements

Julrat, Sakol,

U.S. Department of Agriculture, Agricultural Research Service, Russell Research Center, 950 College Station Rd, Athens, GA 30605

Trabelsi, Samir,

U.S. Department of Agriculture, Agricultural Research Service, Russell Research Center, 950 College Station Rd, Athens, GA 30605

Corresponding author: Sakol Julrat, email: sakol.julrat@gmail.com; phone: +1-706-546-3157; fax: +1-706-546-3607

Abstract

A density-independent algorithm for moisture content determination in sawdust, based on a one-port reflection measurement technique is proposed for the first time. Performance of this algorithm is demonstrated through measurement of the dielectric properties of sawdust with an open-ended half-mode substrate-integrated waveguide (HMSIW) sensor. For accurate measurement of the dielectric properties of sawdust, the HMSIW sensor was calibrated by using a three-material calibration technique, with air, water and 25% ethanol aqueous solution. For moisture determination, a density-independent calibration function expressed in terms of the dielectric properties was used. Both moist and dry bulk densities were considered for the complex-plane representation of the dielectric properties. Results of moisture prediction, relative to each complex-plane representation were found to be similar at 5 GHz and 23 °C with the standard errors of performance of 0.955% and 0.957%, respectively.

Keywords: Dielectric properties, open-ended rectangular waveguide, substrate waveguide sensor, moisture content, sawdust.

Nomenclature

a_f	Slope of regression line of complex-plane representation of the dielectric properties each divided by moist bulk density
a'_f	Slope of regression line of complex-plane representation of the dielectric properties each divided by dry bulk density
Δe_i	Difference between predicted value and that determined by a standard oven method for i^{th} sample
e_A	Average value of Δe_i
ε	Dielectric properties of sawdust
ε_A	Dielectric properties of air
ε_B	Dielectric properties of water
ε_C	Dielectric properties of 25% ethanol aqueous solution
ε'	Dielectric constant
ε''	Dielectric loss factor
HMSIW	Half-mode substrate-integrated waveguide
M	Moisture content, wet basis (%)
m_{sawdust}	Mass of sawdust (g)
m_{water}	Mass of water (g)
m_{wood}	Mass of wood (g)
N	Number of samples
ψ	Density-independent function
ψ_{dry}	Density-independent function of dry bulk density
ψ_{moist}	Density-independent function of moist bulk density
ρ_{dry}	Dry bulk density (g cm^{-3})
ρ_{moist}	Moist bulk density (g cm^{-3})
R^2	Coefficient of determination
Γ	Reflection coefficient of sawdust
Γ_A	Reflection coefficient of air
Γ_B	Reflection coefficient of water
Γ_C	Reflection coefficient of 25% ethanol aqueous solution
SEP	Standard error of performance
SD	Standard deviation
v_{air}	Volume of air (cm^3)
v_{sawdust}	Volume of sawdust (cm^3)
v_{water}	Volume of water (cm^3)
v_{wood}	Volume of wood (cm^3)

1 **1. Introduction**

2 Sawdust is a common raw material in bioenergy production (Nyström & Dahlquist, 2004; Jensen et
3 all, 2006; Kaliyan, & Morey, 2009). The advantage of sawdust biomaterial is the cost per power unit,
4 which is lower than that of other energy sources. Typically, higher efficiency in converting sawdust into
5 heat is obtained for pelletised sawdust with moisture content ranging from 6% to 8% (wet basis). The
6 process of converting sawdust into pellets involves both drying and densification. Normally, the moisture
7 content of the raw sawdust is around 15-45% (wet basis) and it is dried to about 10% (wet basis) before
8 densification. During the densification (pelleting) process, moisture is added to bring the sawdust to 14-15%
9 moisture content. After that, pellets are dried to a moisture content of about 6-8% (wet basis). Therefore,
10 moisture content is a critical parameter as it relates to the quality of the pellets and energy consumption for
11 pelleting and drying.

12 Physically, sawdust is a heterogeneous material with porous structure similar to that of wood. The
13 main constituents of sawdust material are wood, water and air. In this paper, moisture content is the
14 parameter of interest. Recently, a broadband microwave technique (Paz, Trabelsi, Nelson & Thorin, 2011)
15 was used for measuring the dielectric properties of sawdust samples of different moisture contents. The
16 measured dielectric properties of sawdust were found to increase linearly with the volumetric moisture
17 content of the sawdust. This provides the basis for developing a microwave technique for determining
18 moisture content in sawdust. Typically, the dielectric properties of the particular materials are dependent
19 on bulk density (Nelson, 1994; Trabelsi, Krazsewski & Nelson, 1998a; Trabelsi, Krazsewski & Nelson,
20 2001; Trabelsi & Nelson, 2003). It would be advantageous to have a density-independent algorithm for
21 moisture content determination in sawdust.

22 In this paper, a density-independent algorithm for moisture content determination in sawdust,
23 based on reflection measurements, is proposed for the first time. In section 2, a low-cost open-ended half-
24 mode substrate-integrated waveguide (HMSIW) sensor with grounded flange is described, and details of
25 its use for measuring the dielectric properties of sawdust are given. The density-independent calibration
26 function was developed, based on complex-plane representations of the dielectric properties, each divided
27 by either moist or dry bulk density (Trabelsi, Krazsewski & Nelson, 1998a; Trabelsi & Nelson 1998b;
28 Trabelsi & Nelson 1998c; Trabelsi, Paz & Nelson, 2013; McKeown, Trabelsi & Tollner, 2016; McKeown,
29 Trabelsi, Nelson & Tollner, 2017). Results of moisture prediction by using both approaches (moist and dry
30 bulk density) are presented and the performance of each algorithm is given in section 3.

31 **2. Materials and Methods**

2.1. Open-ended half-mode substrate integrated waveguide (HMSIW) sensor

The open-ended HMSIW sensor (Fig.1), fed by a microstrip line (Lai, Fumeaux, Hong, & Vahldieck, 2009), was used as the open-ended waveguide sensor with a grounded flange (Kempin, Ghasr, Case & Zoughi, 2014) for measuring the dielectric properties of sawdust. To avoid the ionic conduction effect (Paz, Trabelsi, Nelson & Thorin, 2011), the operating frequency of the sensor was selected to be above 4 GHz. Therefore, the dimensions of the sensor are as shown in Fig. 1. The aperture waveguide of the HMSIW was inserted into an opening in the grounded flange and soldered to both sides of the HMSIW. An acrylic conformal coating was applied to the waveguide aperture to protect from the material being measured. The dielectric properties of the sawdust (ϵ) were determined by measuring the reflection coefficient (Γ) of three materials of known dielectric properties and that of sawdust by using the following expression (Wei, & Sridhar, 1991):

$$\frac{(\epsilon - \epsilon_A)(\epsilon_B - \epsilon_C)}{(\epsilon - \epsilon_B)(\epsilon_C - \epsilon_A)} = \frac{(\Gamma - \Gamma_A)(\Gamma_B - \Gamma_C)}{(\Gamma - \Gamma_B)(\Gamma_C - \Gamma_A)} \quad (1)$$

where ϵ and Γ with subscripts A, B and C represent the dielectric properties of air, water and 25% ethanol aqueous solution and their respective measured reflection coefficients. Fig. 2 shows the predicted results for the dielectric properties of the 50% ethanol aqueous solution. The predicted results agree well with those measured with an Agilent Technologies 85070E dielectric probe for frequencies between 4.5 GHz to 5.25 GHz and corresponding to the dominant mode of the HMSIW.

Fig. 1- Half-mode substrate integrated waveguide (HMSIW) sensor with grounded flange.

Fig. 2 - Validation results for the open-ended HMSIW sensor with measurement on 50% ethanol aqueous solution at room temperature (23°C).

2.2. Dielectric properties measurement

Fig. 3 shows the measurement setup. The plastic container for liquid samples was mounted on the top of the grounded flange. A high-quality flexible coaxial cable connected the open-ended HMSIW sensor to the automatic network analyser (ANA, ENA series E5071C). The one-port reflection coefficient measurement was performed with the ANA. Three materials, i.e, air, water and 25% ethanol aqueous solution, were used to calibrate the open-ended HMSIW sensor.

Dielectric properties of eight sawdust samples with different moisture contents were measured with the open-ended HMSIW sensor. Each sawdust sample was loaded into the container (70 mm x 120 mm x 50 mm), with the sawdust resting on the waveguide. The sawdust sample was 50-mm thick. Effect of bulk density on dielectric measurements was investigated by varying the compaction of sawdust. For the low density, the sawdust sample was carefully poured into the container without any pressure on the sawdust. To obtain higher densities, constant loads of 0.5 kg, 1.0 kg and 5 kg were applied for packing the sawdust sample while adding more material to maintain the 50-mm thickness. For each sample, bulk moist densities corresponding to the different loads is given in Table 1. For accurate measurements, it is important to ensure sample uniformity around the aperture of the open-ended HMSIW.

Fig. 3 - Measurement setup.

2.3. Density-independent algorithm

The density-independent calibration function for predicting moisture content in porous materials is very well known for the 2-port transmission measurement technique (Trabelsi, Krazewski & Nelson, 1998a; Trabelsi & Nelson 1998b; Trabelsi & Nelson 1998c; Trabelsi, Paz & Nelson, 2013; McKeown, Trabelsi & Tollner, 2016; McKeown, Trabelsi, Nelson & Tollner, 2017). It is defined in terms of the dielectric properties as (Trabelsi, Krazewski & Nelson, 1998a):

$$\psi = \sqrt{\frac{\epsilon''}{\epsilon'(a_f \epsilon' - \epsilon'')}} \quad (2)$$

where ϵ' , ϵ'' and a_f are the dielectric constant, the dielectric loss factor and slope determined from the complex-plane representation of the dielectric properties each divided by either moist or dry bulk density (ρ_{moist}) or (ρ_{dry}). To the authors' knowledge, there is no report on the density-independent calibration function used with the 1-port measurement technique. Both the dielectric properties data divided by moist bulk density and the data divided by dry bulk density can be fitted by a linear regression of the form:

$$\frac{\epsilon''}{\rho_{moist}} = a_f \left[\frac{\epsilon'}{\rho_{moist}} - k \right] \quad (3)$$

$$\frac{\epsilon''}{\rho_{dry}} = a'_f \left[\frac{\epsilon'}{\rho_{dry}} - k' \right] \quad (4)$$

where a_f, k are the slope and x-axis intercept for equation (3) and a'_f, k' are those for equation (4). The moist and dry bulk densities are defined as follows:

$$\rho_{moist} = \frac{m_{sawdust}}{v_{sawdust}} = \frac{m_{water} + m_{wood}}{v_{water} + v_{wood} + v_{air}} \quad (5)$$

$$\rho_{dry} = \frac{m_{sawdust}}{v_{sawdust}} = \frac{m_{sawdust} - m_{sawdust} * M}{v_{water} + v_{wood} + v_{air}} \quad (6)$$

where M is the oven moisture content (ASTM, 2006) of the sawdust, m and v with subscripts *wood*, *water* and *air* represent the mass and volume of the wood, water and air in the sawdust, respectively. This means that dividing the dielectric properties by ρ_{dry} doesn't remove the effect of water density from the sawdust sample while dividing by ρ_{moist} does.

Calibration methods for non-destructive determination of moisture content from microwave measurements were used successfully for cereal grain and oilseed (Trabelsi and Nelson 2004). Among these methods, the density-independent calibration function ψ was found to increase linearly with moisture content. Therefore, a linear regression can be used to correlate ψ with moisture content:

$$\psi_{\rho_{moist}, \rho_{dry}} = aM + b \quad (7)$$

where a and b are the slope and intercept for the linear correlation between ψ and moisture content. Hence, moisture content can be determined from equation (7) as:

$$M = \frac{\psi_{\rho_{moist}, \rho_{dry}} - b}{a} \quad (8)$$

3. Results and discussion

3.1. Frequency dependence

Figs.4 and 5 show the frequency dependence of the measured dielectric properties of sawdust samples with different moisture contents at low density (average $\rho_{moist} = 0.21 \text{ g cm}^{-3}$) and high density (average $\rho_{moist} = 0.29 \text{ g cm}^{-3}$), respectively. In general, the dielectric constant remained almost constant

with frequency. The dielectric constant represents the energy storage caused by the dielectric polarisation in the sawdust sample, which is influenced by the water, wood and air, respectively. From Figs. 4 (a) and 5(a), the dielectric constant increases with the moisture content for both low and high densities. Moreover, the dielectric constant for the higher density samples is greater than that of lower density because of higher water and wood contents but less air in the higher density samples.

The dielectric loss factor represents the losses in sawdust sample often dissipated in the form of heat. From Figs. 4(b) and 5(b) the dielectric loss factor increases with frequency with higher slopes for higher moisture levels.

(a)

(b)

Fig. 4 - Frequency dependence of the dielectric properties of sawdust at indicated moisture contents and low density level (average $\rho_{moist} = 0.21 \text{ g cm}^{-3}$) at room temperature (23°C): (a) dielectric constant and (b) dielectric loss factor.

(a)

(b)

Fig. 5 - Frequency dependence of the dielectric properties of sawdust at indicated moisture contents and high density level (average $\rho_{moist} = 0.29 \text{ g cm}^{-3}$) at room temperature (23°C): (a) dielectric constant and (b) dielectric loss factor.

3.2. Density dependence

Fig. 6 shows the moisture dependence of the dielectric properties from low to high densities at 5.0 GHz and 23° C and those of the dielectric properties, each divided by moist bulk density or dry bulk density. In Fig. 6 (a), the dielectric properties increase linearly with moisture content for each density and the higher the moisture content the more variation in the dielectric properties. This phenomenon reflects the density dependence behaviour at various moisture contents on the sawdust sample. Data presented in Fig. 6(a) are also listed in Table 1.

Fig. 6 (b) shows the dielectric properties divided by moist bulk density or dry bulk density. Both the dielectric constant and dielectric loss factor each divided by moist or dry bulk densities are nearly linearly with moisture content. The effect of density is more apparent on the dielectric constant than the dielectric loss factor. This implies that the dielectric constant is more density dependent than the dielectric loss factor.

Table 1- Dielectric properties at various densities at 5 GHz and 23 °C.

Moisture content (%)	Constant load 0 kg, Average $\rho_{moist} = 0.21 \text{ g cm}^{-3}$						Constant load 0.5 kg, Average $\rho_{moist} = 0.24 \text{ g cm}^{-3}$					
	ρ_{dry}	ρ_{moist}	ϵ'	SD. (ϵ')	ϵ''	SD. (ϵ'')	ρ_{dry}	ρ_{moist}	ϵ'	SD. (ϵ')	ϵ''	SD. (ϵ'')
6.8	0.18	0.20	1.496	0.009	0.023	0.008	0.21	0.23	1.532	0.008	0.032	0.007
9.2	0.19	0.21	1.637	0.024	0.067	0.005	0.21	0.23	1.589	0.031	0.065	0.007
12.0	0.18	0.21	1.584	0.054	0.093	0.007	0.20	0.23	1.662	0.045	0.107	0.004
14.0	0.18	0.21	1.707	0.030	0.116	0.006	0.22	0.25	1.845	0.033	0.134	0.011
16.0	0.18	0.21	1.796	0.028	0.144	0.006	0.20	0.24	1.892	0.033	0.166	0.003
19.5	0.17	0.21	1.900	0.035	0.181	0.002	0.19	0.24	1.998	0.025	0.216	0.014
20.4	0.17	0.21	1.962	0.033	0.196	0.012	0.20	0.25	2.134	0.027	0.231	0.006
22.8	0.15	0.19	1.942	0.043	0.192	0.010	0.18	0.24	2.133	0.040	0.240	0.005

Moisture content (%)	Constant load 1.0 kg, Average $\rho_{moist} = 0.26 \text{ g cm}^{-3}$						Constant load 5.0 kg, Average $\rho_{moist} = 0.29 \text{ g cm}^{-3}$					
	ρ_{dry}	ρ_{moist}	ϵ'	SD. (ϵ')	ϵ''	SD. (ϵ'')	ρ_{dry}	ρ_{moist}	ϵ'	SD. (ϵ')	ϵ''	SD. (ϵ'')
6.8	0.23	0.24	1.559	0.007	0.041	0.004	0.25	0.26	1.615	0.003	0.043	0.003
9.2	0.23	0.25	1.620	0.022	0.072	0.006	0.24	0.27	1.673	0.019	0.077	0.005
12.0	0.22	0.25	1.731	0.023	0.112	0.001	0.26	0.30	1.807	0.019	0.126	0.001
14.0	0.23	0.27	1.930	0.021	0.147	0.009	0.25	0.29	2.007	0.017	0.156	0.008
16.0	0.23	0.27	1.996	0.022	0.191	0.001	0.24	0.29	2.088	0.019	0.210	0.001
19.5	0.21	0.27	2.108	0.010	0.241	0.007	0.24	0.29	2.253	0.007	0.280	0.002
20.4	0.21	0.27	2.250	0.021	0.260	0.001	0.23	0.29	2.387	0.019	0.289	0.001
22.8	0.20	0.26	2.293	0.023	0.280	0.001	0.23	0.29	2.486	0.019	0.339	0.001

(a)

(b)

Fig. 6 - Moisture dependence of the dielectric properties of sawdust at 5.0 GHz and room temperature (23°C): (a) at indicated average densities, (b) divided by either moist or dry bulk density.

3.3. Density-independent algorithm

Fig.7 shows the complex-plane representations of the dielectric properties each divided by either the moist or dry bulk densities at 5 GHz. Both complex-plane representations indicate that dividing by moist and dry bulk density leads to similar trends with similar values for the slope and x-axis intercept. Equations (3) and (4) were used to correlate the dielectric properties each divided by either moist or dry density. The fitting parameters and coefficient of determination of these equations are listed in Table 2. At low moisture contents, both straight lines are very close because the values of moist and dry bulk densities are similar. When the moisture content increases the straight lines diverge. The correlation between the moist bulk density and the dry bulk density is shown in Fig 8. Because of the range of moisture content investigated in this study (less than 23%), the moist bulk density has a linear relationship with the dry bulk density and can be expressed as follows:

$$\rho_{moist} = 1.0260 * \rho_{dry} + 0.03 \quad R^2 = 0.8317 \quad (9)$$

Fig. 9 shows that the density-independent function ψ increased linearly with oven moisture content (ASTM, 2006). Linear regression can be used to correlate ψ with moisture content as shown by Eq. (2). The fitting parameters and coefficient of determination are listed in Table 3. The coefficient determination of $\psi_{\rho_{moist}}$ and $\psi_{\rho_{dry}}$ show high correlation between ψ and moisture content with R^2 of 0.9201 and 0.9238, respectively. This means that both $\psi_{\rho_{moist}}$ and $\psi_{\rho_{dry}}$ can be used for determining moisture content of sawdust from low to high densities by using parameters in Table 3 with equation (8).

Fig.7 - Complex-plane representation of the dielectric properties of sawdust each divided either by bulk density or dry density at 5 GHz and at the room temperature (23°C).

Fig.8 - Correlation between moist bulk density and dry bulk density at room temperature (23°C).

Fig.9 - Variation of density-independent calibration functions with moisture content at 5 GHz and at room temperature (23°C).

Table 2 - Regression constants and coefficients of determination for equations (3) and (4).

Statistics		5.0 GHz
Moist Bulk density Equation(3)	a_f	0.2480
	k	5.1492
	R^2	0.7950
Dry bulk density Equation(4)	a'_f	0.2196
	k'	5.6562
	R^2	0.8979

Table 3 - Regression Constants and coefficients of determination for calibration function equation (7)

Statistics		5.0 GHz
$\psi_{\rho_{moist}}$ Equation(7)	a	0.0239
	b	0.1340
	R^2	0.9201
$\psi_{\rho_{dry}}$ Equation(7)	a	0.0283
	b	0.1209
	R^2	0.9238

3.4. Algorithm validation

To evaluate the performance of the density-independent calibration function, different sawdust samples of different moisture contents were prepared and measured at four levels of moist bulk density (average $\rho_{moist} = 0.21 \text{ g cm}^{-3}$, 0.24 g cm^{-3} , 0.26 g cm^{-3} and 0.29 g cm^{-3}). Fig.10 shows the predicted results at 5 GHz versus the moisture content that was obtained with a standard oven method (ASTM, 2006). The predicted results agree well with the standard oven method for moisture contents ranging from 10% to 20% for both the moist and dry bulk density predictions. The standard error of performance (*SEP*) for moisture content determined with equation (8) was calculated as follows:

$$SEP = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (\Delta e_i - e_A)^2} \quad (10)$$

where N is number of samples, Δe_i is the predicted error between equation (8) and a standard oven method for the i th sample, and $e_A = (\sum_{i=1}^N \Delta e_i)/N$. The *SEP* was 0.955% for $\psi_{\rho_{moist}}$ and 0.957% for $\psi_{\rho_{dry}}$.

From the predicted results, the density-independent calibration function developed by using the moist bulk density and dry bulk density were similar.

Fig.10 - Predicted moisture content of the sawdust at room temperature (23°C) versus moisture determined by standard oven method.

4. Conclusions

A density-independent algorithm for determining moisture content of sawdust, based on a microwave reflection technique, has been developed and tested. The technique proposed in this paper allows one to determine the moisture content of sawdust from measurement of the dielectric properties determined from measurement of the reflection coefficient at a single frequency. For the definition of the density-independent calibration function, complex-plane representations of the dielectric properties divided by either moist or dry bulk density were considered. Calculation of the standard errors of performance for moisture prediction in sawdust samples by using the two functions were very close, ie. 0.955% and 0.957%. The reflection-based algorithm, coupled with the low cost of the sensing device, show potential for the use of this method for in-process moisture determination in sawdust during the densification process where moisture content ranges from 10% to 20%.

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References

- ASTM. (2006). Standard Test Method for Moisture Analysis of Particulate Wood Fuels E871-82.
- Jensen, P. D., Hartmann, H., Böhm, T., Temmerman, M., Rabier, F., & Morsing, M. (2006). Moisture content determination in solid biofuels by dielectric and NIR reflection methods. *Biomass and bioenergy*, 30(11), 935-943.
- Kaliyan, N., & Morey, R. V. (2009). Factors affecting strength and durability of densified biomass products. *Biomass and bioenergy*, 33(3), 337-359.
- Kempin, M., Ghasr, M. T., Case, J. T., & Zoughi, R. (2014). Modified waveguide flange for evaluation of stratified composites. *IEEE Transactions on Instrumentation and Measurement*, 63(6), 1524-1534.
- Lai, Q., Fumeaux, C., Hong, W., & Vahldieck, R. (2009). Characterization of the propagation properties of the half-mode substrate integrated waveguide. *IEEE Transactions on Microwave Theory and Techniques*, 57(8), 1996-2004.
- McKeown, M. S., Trabelsi, S., & Tollner, E. W. (2016). Effects of temperature and material on sensing moisture content of pelleted biomass through dielectric properties. *Biosystems Engineering*, 149, 1-10.
- McKeown, M. S., Trabelsi, S., Nelson, S. O., & Tollner, E. W. (2017). Microwave sensing of moisture in flowing biomass pellets. *Biosystems Engineering*, 155, 152-160.
- Nelson, S. O. (1983). Density dependence of the dielectric properties of particulate materials. *Transactions of the ASAE*, 26(6), 1823-1825.
- Nelson, S. O. (1994). Measurement of microwave dielectric properties of particulate materials. *Journal of food engineering*, 21(3), 365-384.
- Nyström, J., & Dahlquist, E. (2004). Methods for determination of moisture content in woodchips for power plants—a review. *Fuel*, 83(7), 773-779.

- 1 Paz, A. M., Trabelsi, S., Nelson, S. O., & Thorin, E. (2011). Measurement of the dielectric properties of
2 sawdust between 0.5 and 15 GHz. *IEEE Transactions on Instrumentation and Measurement*,
3 60(10), 3384-3390.
- 4 Trabelsi, S., Krazewski, A. W., & Nelson, S. O. (1998a). New density-independent calibration function
5 for microwave sensing of moisture content in particulate materials. *IEEE Transactions on*
6 *Instrumentation and Measurement*, 47(3), 613-622.
- 7 Trabelsi, S., & Nelson, S. O. (1998b). Density-independent functions for on-line microwave moisture
8 meters: a general discussion. *Measurement Science and Technology*, 9(4), 570-578.
- 9 Trabelsi, S., Kraszewski, A. W., & Nelson, S. O. (1998c). A microwave method for on-line determination
10 of bulk density and moisture content of particulate materials. *IEEE Transactions on*
11 *Instrumentation and Measurement*, 47(1), 127-132.
- 12 Trabelsi, S., Kraszewski, A. W., & Nelson, S. O. (2001). New calibration technique for microwave
13 moisture sensors. *IEEE Transactions on Instrumentation and Measurement*, 50(4), 877-881.
- 14 Trabelsi, S., & Nelson, S. O. (2003). Free-space measurement of dielectric properties of cereal grain and
15 oilseed at microwave frequencies. *Measurement Science and Technology*, 14(5), 589-600.
- 16 Trabelsi, S., & Nelson, S. O. (2004). Calibration methods for nondestructive microwave sensing of
17 moisture content and bulk density of granular materials. *Transactions of the ASAE*, 47(6), 1999-
18 2008.
- 19 Trabelsi, S., Paz, A. M., & Nelson, S. O. (2013). Microwave dielectric method for the rapid, non-
20 destructive determination of bulk density and moisture content of peanut hull pellets. *Biosystems*
21 *engineering*, 115(3), 332-338.
- 22 Wei, Y. Z., & Sridhar, S. (1991). Radiation-corrected open-ended coax line technique for dielectric
23 measurements of liquids up to 20 GHz. *IEEE Transactions on Microwave Theory and Techniques*,
24 39(3), 526-531.