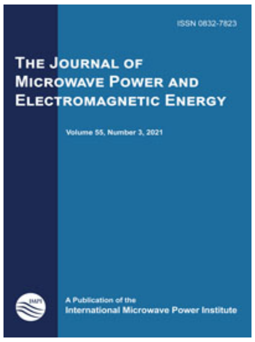

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RESEARCH ARTICLE

Determination of foreign-material content in uncleaned peanuts by microwave measurements and machine learning techniques

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ABSTRACT

Foreign-material content determination in uncleaned peanuts based on dielectric properties and bulk density measurements by microwave techniques is presented in this paper. A microwave free-space transmission technique was used at 10 GHz. Two measurement systems for measuring the dielectric properties of cleaned unshelled peanuts (nine-peanut pods) and uncleaned unshelled peanuts placed in polycarbonate sample holder (12.1 cm × 21 cm × 20.5 cm) were developed and integrated in one single measuring unit. The nine-peanut-pods system provided the cleaned unshelled peanuts moisture content which was used in the algorithms for foreign material content determination. The dielectric properties and bulk density measurements of the uncleaned unshelled peanut sample were related to the foreign-material content. These parameters, namely bulk density and dielectric properties of uncleaned peanuts and cleaned unshelled moisture content were supplied to machine learning algorithms, linear regression technique and artificial neural network algorithms. Results obtained with the artificial neural network algorithm showed the best estimate of foreign material content with a standard error of performance of 1.36% compared to that obtained with the linear regression algorithm with a standard of performance of 2.39%.

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KEYWORDS
Microwave sensing; foreign material content; dielectric properties; bulk density; uncleaned peanuts; machine learning

1. Introduction

The amount of unwanted foreign materials in harvested peanuts has to be determined for peanut grading at the buying point. If the foreign-materials content is higher than the threshold set by the peanut buying point, the peanut load is sent for further cleaning and the farmer incurs the cost for such cleaning. It would be advantageous for the farmer to determine the foreign-materials content in the field and hence avoid any costs associated with transportation and cleaning. In this paper, a method and sensor for real-time determination of foreign materials content is proposed. It is

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based on dielectric properties at a single microwave frequency and the use of machine learning techniques. Currently, uncleaned peanuts are transported by peanut framers to the buying point in a trailer. At the buying point, a pneumatic sampler (Dickens 1964) is used to extract samples from the uncleaned peanuts from the trailer. About 4000 g of uncleaned peanuts are sampled from the trailer. A divider hopper is used to split the uncleaned peanut sample into two bags, 2000 g each. Bag 1 is used in the grading room while bag two (check sample) is reserved in case any mistakes occur in grading bag 1. To determine foreign material content, foreign materials, such as peanut shells, peanut raisins (shriveled immature peanuts), sticks, stones and corncobs, etc., are manually collected from the uncleaned peanut sample (bag 1) by hand. This process is time consuming and can be affected by human errors (AMS USDA 2019, p. 32). If a peanut load contained more than 10.49% foreign material (AMS USDA 2019, p. 46), it will be returned to the farmer for cleaning, either manually or automatically (Carter 1951, 1981), and the buy-sell process will be terminated. Moreover, the price for the peanuts with foreign materials greater than 10.49% will be reduced compared to that for cleaned peanuts, because the buying point will charge the grower for removing the foreign materials. Therefore, the percentage of foreign material is a key variable in the buy-sell process. An accurate and rapid foreign-material-content meter would be an advantage for the farmer in knowing the percentage of foreign material before transporting the peanuts to the buying point. Furthermore, it would be most helpful in the peanut grading process at the peanut buying point.

Microwave free-space measurement techniques are well known for nondestructive and instantaneous moisture content determination (Trabelsi et al. 2010, 2016, 2019). Therefore, a transmission-free-space microwave sensing technique (Julrat and Trabelsi 2019) is a good candidate measurement technique that can be developed for foreign material content determination from measurement of the dielectric properties at a single microwave frequency. Recently, it was observed that the dielectric constant (ε') of cleaned unshelled peanuts mixed with a single type of foreign material decreases with increasing the percentage of foreign materials such as peanut shells, peanut raisins and sticks (Julrat and Trabelsi 2019). However, the dielectric constant increases with the percentage of stones foreign material. The dielectric loss factor (ε'') remained constant with increasing percentages of peanut shells, peanut raisins and sticks but it increased with increasing percentages of stones foreign materials (Julrat and Trabelsi 2019). Furthermore, the influence of multiple types of foreign materials mixed with cleaned unshelled peanuts has been reported (Julrat and Trabelsi 2021). The dielectric constant of mixtures of pods mixed with multiple-type foreign materials is mainly influenced by peanut shells, sticks, stones and peanut raisins, respectively. For better understanding the dielectric response of different mixtures of unshelled peanut pods and foreign materials, the logarithmic dielectric mixture equation can be used to estimate the effective dielectric constant of single and multiple types of foreign material mixed with cleaned unshelled peanuts. These relationships are useful in developing microwave based foreign material sensing.

In this paper, a nondestructive free-space microwave measurement system and algorithms (linear regression and neural network) for foreign-material determination are described. The measurement system consisted of a four-pairs-of-antennas system for measurements on mixtures of unshelled peanuts and foreign materials (Julrat and Trabelsi 2021) and a system consisting of two antennas for measurements on nine cleaned unshelled peanuts which was exclusively developed for this application. Information on foreign materials in uncleaned peanuts was obtained from measurement of the dielectric properties with the four-pairs-of-antennas system, while measurement of the dielectric properties of the nine unshelled peanuts provided their moisture content. By combining all the information collected with the two systems, algorithms were developed for foreign materials determination. These algorithms were developed based on the assumption that there is a significant difference in the dielectric properties of peanut samples with and without foreign materials.

2. Materials and methods

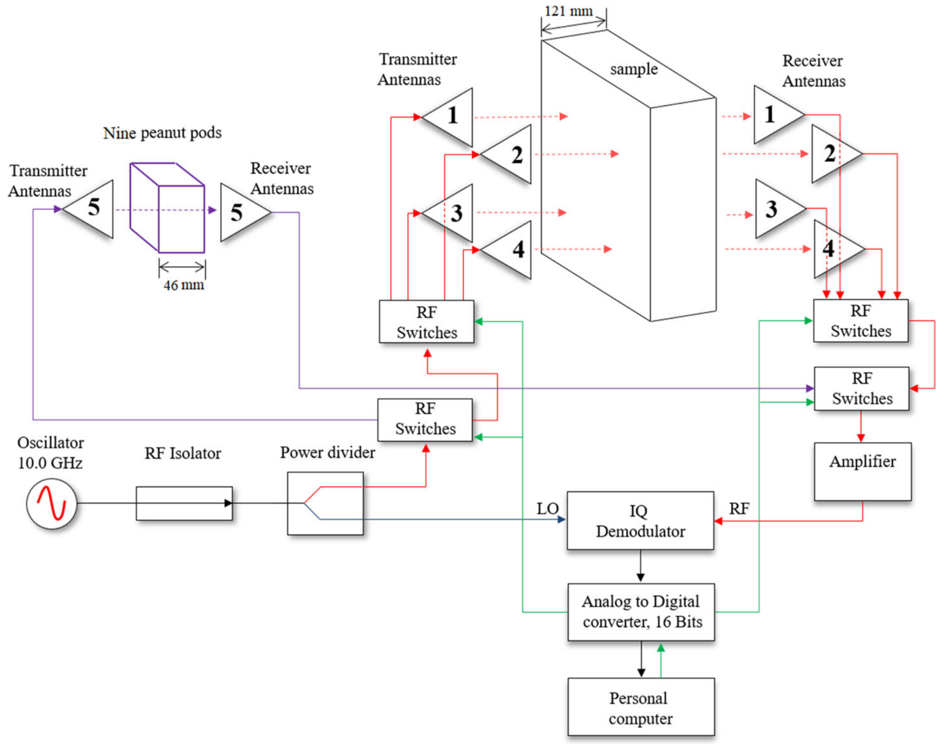
2.1. Nondestructive free-space microwave measurement technique

A nondestructive free-space microwave measurement system is proposed for foreign-materials content determination. Figure 1(a) shows the block diagram of the proposed system. A modification of the four-pairs-of-antenna measurement system presented in (Julrat and Trabelsi 2019) was made. A fifth-pair of antennas and two switches were added to the four-pairs-of-antenna measurement system and served as the nine-peanut-pods measurement system. The microwave components of the proposed system are similar to those described previously (Julrat and Trabelsi 2019). It should be noted that the nine-peanut-pods measurement system is first introduced in this work. Therefore, the dielectric properties of foreign materials mixed with the cleaned unshelled peanuts were measured with the four-pairs-of-antenna measurement system while the dielectric properties of the cleaned unshelled peanuts were measured by the nine-peanut-pods measurement system. Measurement results from the combined system were used for extracting the foreign material content in the peanut sample.

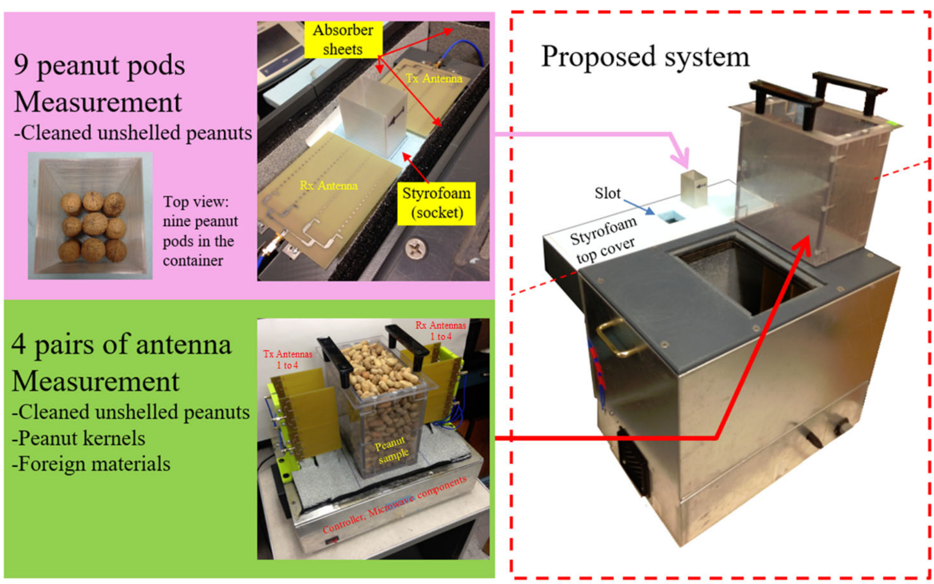
Figure 1(b) shows a perspective view of the proposed system. Nine peanut pods were loaded into a sample container made of clear n-Gen co-polyester 3D printing filament materials (size 46 mm × 46 mm × 60 mm). The sample container was placed between the transmitting and receiving antennas with 5 mm distance from the antennas. Microwave absorber sheets were placed on the sides and back of the antennas to avoid multiple reflections. Styrofoam material was used as a bottom part (socket) and a top cover with a slot was provided for inserting the sample container. The nine-peanut pods measurement system was integrated on the side of the four-pairs of antenna measurement system. Fabrication details and dielectric measurement results for the four-pairs-of-antenna measurement system (container size = 12.1 cm × 21 cm × 20.5 cm) were previously reported (Julrat and Trabelsi 2019).

2.2. Sample preparation

Peanut samples (Runner type) were collected from a buying point in Georgia, USA. The individual peanut pod is of nearly cylindrical shape and contained two kernels



(a)



(b)

Figure 1. Measurement system, (a) block diagram and (b) perspective view.

with an average diameter of about 6 mm. The average length of the unshelled peanut pods was about 25 mm.

Table 1. Portion of foreign materials in the peanut samples from the buying point, by weight.

			Portion of foreign materials (%)				
Sample	Moisture content (%)	Foreign materials (%)	Peanut shells	Peanut raisins	Sticks	Stones	Corncobs
1	6.5	2.5	48	31	9	12	0
2	6.3	1.7	59	29	12	0	0
3	6.3	1.9	64	16	14	6	0
4	6.1	2.5	53	28	12	0	7
5	6.6	3.0	74	17	6	3	0
6	6.2	2.6	57	25	13	5	0
7	6.2	2.8	58	25	8	9	0
Average	6.3	2.4	59	24	11	5	1

2.2.1. Nine-peanut-pods measurement

Samples of cleaned unshelled peanuts (Runner type) of moisture contents ranging from 6% to 20% (wet basis, mass of water divided total mass) were prepared and placed in plastic bags. Each bag contained 30 peanut pods and each pod had two peanut kernels. Reference moisture content was determined by the standard oven-drying technique (ASAE 2002). The initial moisture content of all samples was 6.3%. Different moisture levels were obtained by spraying the peanut pods with a fine mist of deionized water and they were kept in sealed bags for three days in a cold room at 4 °C for moisture equilibration.

To evaluate the performance of moisture determination algorithm, the samples were separated into two sets: A calibration set (28 samples) and a validation set (120 samples). Samples were removed from the cold room and kept at room temperature (23 °C) for 6 hours before measurements. For each measurement series, nine pods were taken from the plastic bag and placed in the container as shown in Figure 1.

2.2.2. Four-pairs-of-antennas measurement

These measurements were based on the standard sample size used in the grading room at the peanut buying point. The inner size of the sample container was 12.1 cm × 21 cm × 20.5 cm. Total weight of the cleaned unshelled peanut sample in the sample container was about 1800 g. The foreign materials mixed with cleaned unshelled peanuts were prepared based on the foreign material proportions encountered at the buying point. Table 1 lists the foreign materials portion (by weight). As shown, the foreign material content was dominated by the peanut shells. From previously reported research (Julrat and Trabelsi 2021), this implies that the dielectric constant of the uncleaned peanut sample is mainly influenced by the peanut shells. From Table 1, the foreign materials portion of peanut shells, peanut raisins, sticks, stones and corncob averaging 59%, 24%, 11%, 5% and 1%, respectively, were used for these measurements.

Seven samples of foreign materials mixed with cleaned unshelled peanuts with foreign material content ranging from 0% to 14% were prepared at about 16% moisture content (wet basis) as a training set. The deionized water spraying technique was used for increasing the moisture content of the peanut samples (initial moisture 6.3%) up to 16% moisture content. Each peanut sample (about 2 kg) was placed in a sealed plastic bag. All samples were kept in a cold room (4 °C) for three days for moisture equilibration. Samples were removed from the cold room and kept at room temperature (23 °C) for 6 hours before measurements. The foreign material was mixed throughout the cleaned unshelled peanuts and the mixed sample was carefully loaded layer by layer to avoid empty air pockets near the corners of the sample container before the measurements (Julrat and Trabelsi 2019).

After that, the samples were dried from the higher moisture level (16% moisture content) to achieve the 14%, 12%, 10%, 8% and 6% moisture levels. For each level, they were exposed to ambient conditions in the laboratory while monitoring the weight loss. Then they were held in a cold room (4 °C) for three days for moisture equilibration. Samples were removed from the cold room and kept at room temperature (23 °C) for 6 hours before measurements. In total, 42 data points were used in the training set.

Seven more samples were prepared by using the procedure described above as a validation set, with foreign material content ranging from 0% to 14%. Moisture contents of these samples were 15%, 13%, 11%, 9%, 8%, 7% and 6%. Furthermore, natural uncleaned peanut samples collected from the buying point were also used as a validation set. The foreign material content of natural samples ranged from 0% to 5%, and moisture content ranged from 6% to 9%. It should be noted that loose peanut kernels (LSKs) can be found in the natural samples. In total, 59 data points were used in the validation set.

2.3. Foreign-material determination algorithm

2.3.1. Linear regression technique

The linear regression algorithm was adopted based on the assumption of a linear relationship between foreign-materials content and measured parameters such as bulk density and dielectric constant (Julrat and Trabelsi 2019). For this work, the linear regression algorithm available in open source software Weka (http://www.cs.waikato.ac.nz/ml/weka/) was used. Using all measured parameters, foreign material can be determined from the following equation:

$$\%\ Foreign\ material = A{*}\rho_{bulk} + B{*}\varepsilon' + C{*}\varepsilon'' + D{*}MC + F \tag{1}$$

where ρ_{bulk} was obtained from the sample holder volume and sample weight measurement, ε' and ε'' were obtained from the four-antenna measurements and MC was obtained from the nine-peanut-pods measurement. A, B, C, D and F are fitting parameters that are determined by the linear regression technique.

2.3.2. Artificial neural network

The artificial neural network was developed to further improve the accuracy of the predicted foreign material content for any nonlinear relationships between foreign-materials content and measured parameters such as bulk density and dielectric constant (Julrat and Trabelsi 2019). The artificial neural network algorithm (Multilayer perceptron) available in open source software Weka (http://www.cs.waikato.ac.nz/ml/weka/) was used. The log sigmoid activation function was used in the hidden layer (3 nodes) and a linear activation function was used at the output node. The input

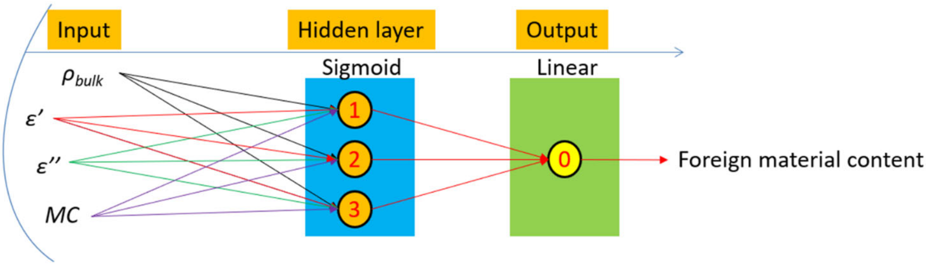


Figure 2. Block daigram of the proposed artificial neural network algorithm.

parameters were the same as those used with the linear regression technique. The block diagram of the artificial neural network is illustrated in Figure 2.

2.4. Standard error calculation

2.4.1. Standard error of calibration

The standard error of calibration (*SEC*) for moisture content was used to determine the effectiveness of the training set. The standard error of calibration was calculated as follows:

$$\mathrm{SEC} = \sqrt{\frac{1}{N - P - 1}\sum\nolimits_{i=1}^{n} (\Delta M_i)^2} \tag{2}$$

where N is number of samples, P is number of independent variables, ΔM_i is the difference between the predicted value of moisture content and that determined by the standard oven method for the i th sample.

2.4.2. Standard error of performance

The standard error of performance (*SEP*) for foreign material content was calculated for the validation sets that were not used in the calibration as follows:

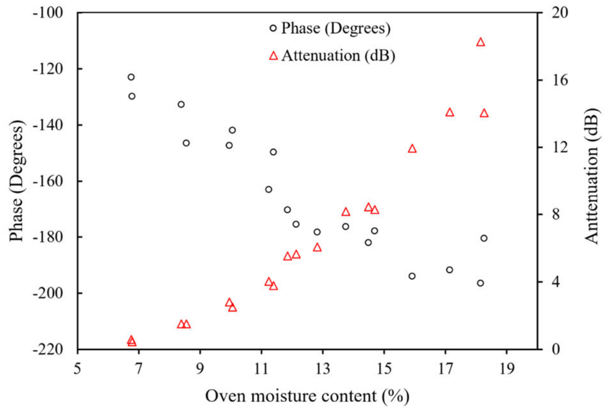
$$\mathrm{SEP} = \sqrt{\frac{1}{N - 1}\sum\nolimits_{i=1}^{n} (\Delta M_i - M)^2} \tag{3}$$

where N is number of samples, ΔM_i is the difference between the predicted value of moisture content and that determined by a standard oven method for the i th sample, and $M = (\sum_{i=1}^{n} \Delta M_i)/N$.

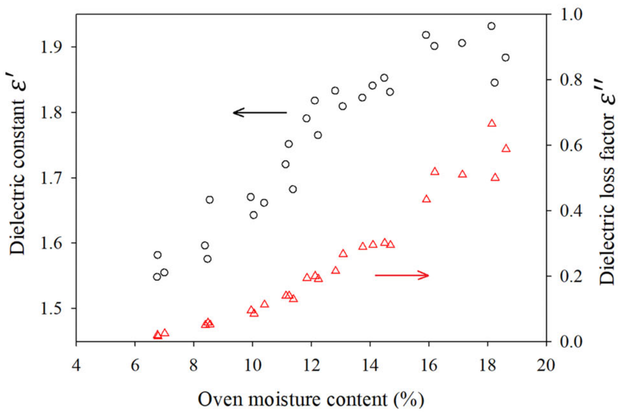
3. Results and discussion

3.1. Nine-peanut-pods measurement

Measured dielectric properties of the nine-peanut-pod samples are shown in Figure 3. Figure 3(a) shows the attenuation and phase shift measurements from the antennas, while the dielectric properties are shown in Figure 3(b). In general, the dielectric properties increased linearly with moisture content (wet basis). The dielectric constant



(a)



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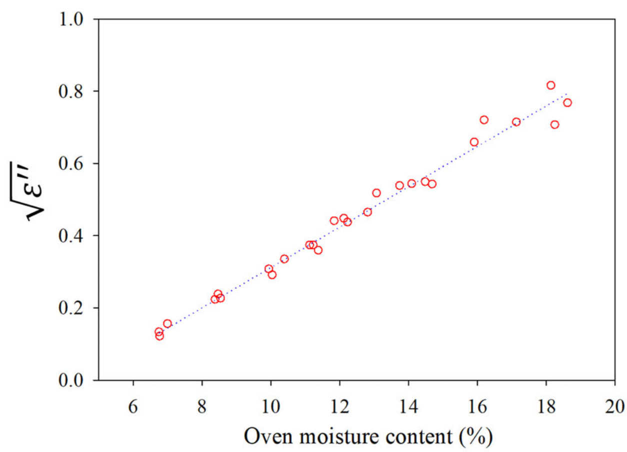

(c)

Figure 3. Nine-peanut-pods measurement results at 10.0 GHz and room temperature (23 °C) as functions of moisture content, (a) attenuation and phase shift measurement from the antenna (b) dielectric properties and (c) square root of dielectric loss factor ($\sqrt{\varepsilon''}$).

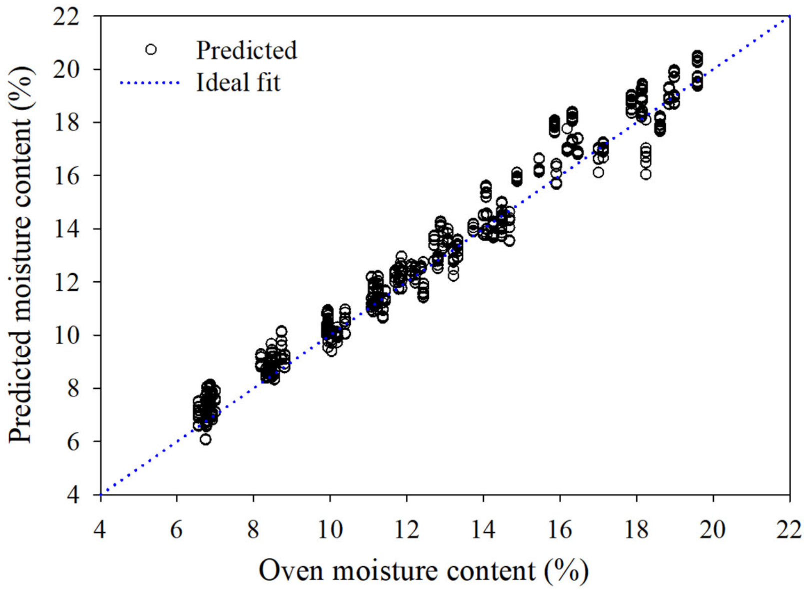

Figure 4. Predicted moisture content of the nine-peanut-pods samples at 10.0 GHz and room temperature (23 °C) versus oven moisture content.

(ε') has a higher variation than the dielectric loss factor (ε'') as shown in Figure 3(b). The square root of dielectric loss factor ($\sqrt{\varepsilon''}$) increased linearly ($R^2 = 0.9837$) with moisture content (wet basis) as shown in Figure 3(c). Therefore, the relationship between the square root of the dielectric loss factor ($\sqrt{\varepsilon''}$) and the oven moisture content can be used for moisture content determination as follows:

$$\sqrt{\varepsilon''} = 0.0559\ MC - 0.2474, \tag{4}$$

$$R^2 = 0.9837 \tag{5}$$

Equation (4) was established based on Figure 3(c). 120 peanut samples were prepared for validation of the moisture content prediction with Eq. (4). Moisture content prediction results using the nine-peanut pods measurement are shown in Figure 4. There was good agreement between the predicted moisture content and the oven-determined moisture content. The *SEC* was 0.583%, wet basis.

3.2. Four-pairs-of antenna measurement

Measurements of initial dielectric properties of the seven samples by using the four-pairs of antennas are listed in Table 2. The bulk density (Trabelsi et al. 1998) and dielectric constant decrease with increasing foreign-materials content. Figure 5 shows the bulk density as a function of percentage of foreign material at various moisture contents. The bulk density decreased with increasing percentage of foreign materials because the bulk densities of the foreign materials are lower than that of the cleaned unshelled peanuts, except for stones foreign material (Julrat and Trabelsi 2021). In

Table 2. Initial dielectric properties measurements for seven samples of foreign materials mixed with cleaned unshelled peanuts at 10.0 GHz and room temperature (23 °C).

Sample	Pods moisture content (%)	Foreign material (%)	**Bulk density (g cm^{-3}) (ρ_{bulk})**	**Dielectric constant (ε')**	**Dielectric loss factor (ε'')**
1	16.4	0.0	0.3296	1.8623	0.3796
2	15.7	2.3	0.3169	1.8532	0.3566
3	16.7	4.5	0.3178	1.8508	0.3913
4	15.7	5.8	0.3104	1.8379	0.3584
5	16.4	8.4	0.2869	1.7911	0.3804
6	16.8	11.7	0.2741	1.8015	0.3919
7	16.3	13.4	0.2797	1.7975	0.3771

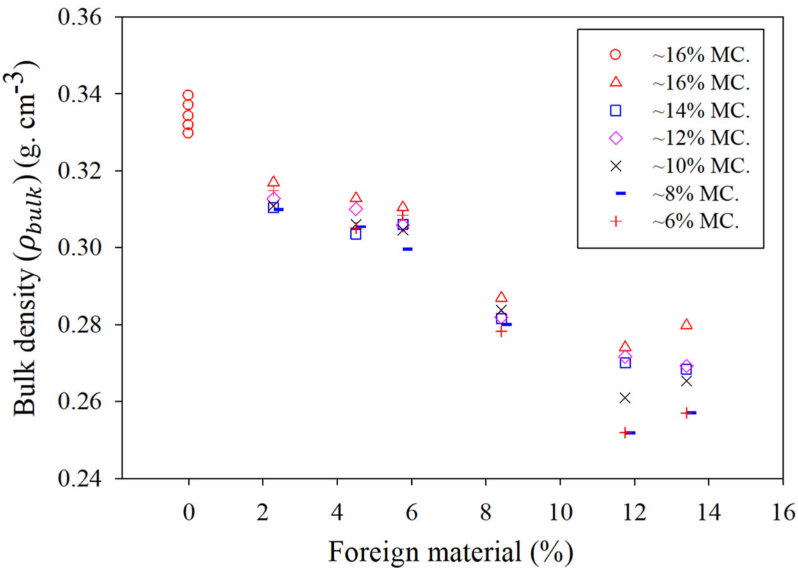

Figure 5. Bulk-density (ρ_{bulk}) as a function of percentage of foreign material at various moisture contents at room temperature (23 °C).

Figure 6, the dielectric constant decreased with increasing percentage of foreign materials and moisture content, while the dielectric loss factor decreased with moisture content but remained relatively constant with the percentage of foreign materials. This implies that moisture was absorbed by the foreign materials as well as by the cleaned unshelled peanuts. From Figures 5 and 6, the linear relationship can be noted between foreign-materials content and measured parameters such as bulk density and dielectric constant.

From the four-antenna-measurement system, knowledge of the bulk density and dielectric constant can be used for foreign materials determination. The dielectric loss factor can be used for estimating the moisture content of the foreign materials mixed with cleaned unshelled peanuts. The effect of moisture content contributes more to the dielectric constant than does that of bulk density. The sample loading procedure could influence the bulk density and hence dielectric properties measurements. For example, if there is an empty air pocket (dielectric constant = 1) in the sample, the

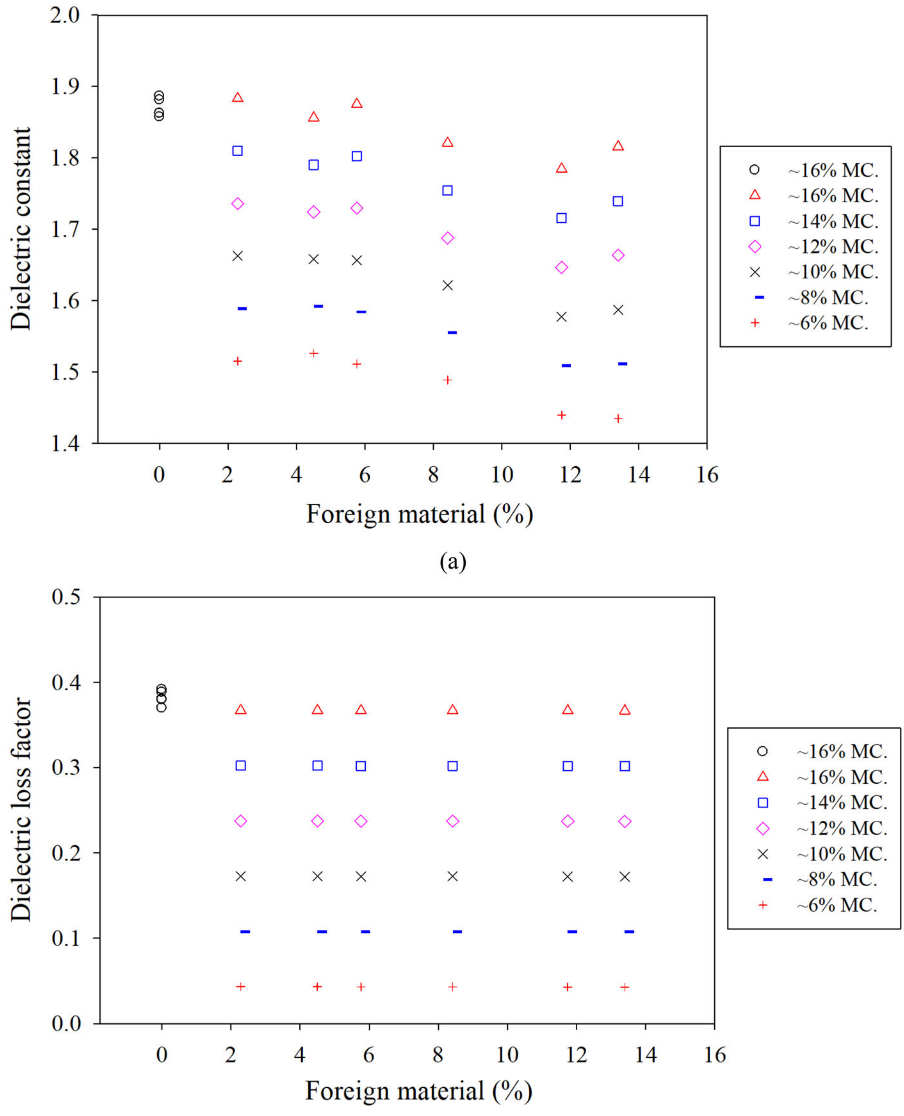

Figure 6. Measured dielectric properties of peanut samples at 10.0 GHz and room temperature (23 °C) as a function of percentage of foreign materials at various moisture contents, (a) dielectric constant and (b) dielectric loss factor.

effect on the measured dielectric constant could be similar to that of the peanut-shells foreign materials (dielectric constant = 1.180).

3.3. Foreign material determination algorithm development

The measurement results for the training data set obtained from nine-peanut-pods and four-pairs-of antenna measurements were used for developing the foreign-material-determination algorithms. The moisture content from the nine-peanut-pods

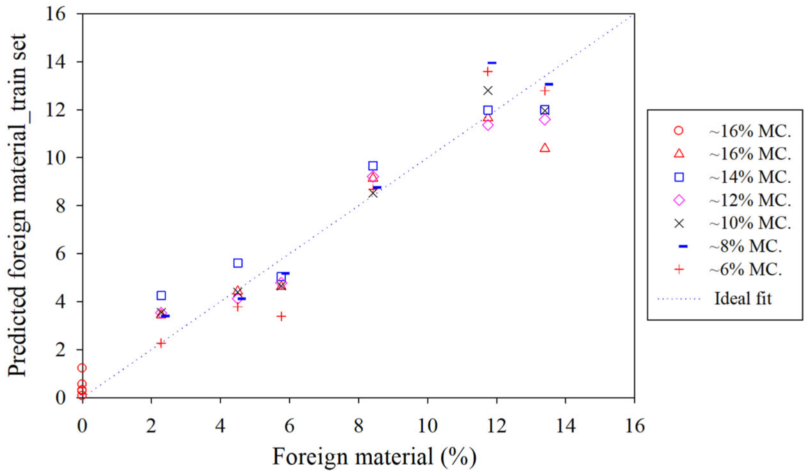

Figure 7. Prediction of foreign-material content with the training data set by using the linear regression algorithm at 10.0 GHz and room temperature (23 °C).

measurement was representative of the moisture content of the cleaned unshelled peanut sample. The dielectric properties and bulk density obtained from the four-antenna measurement system were representative of the mixture of foreign materials and cleaned unshelled peanuts. Machine learning algorithms such as the linear regression and artificial neural network were applied for foreign-materials-content determination.

3.4. Linear regression technique

Using measurement data for the training data set, the linear relationship between foreign-materials content and measured parameters such as bulk density and dielectric constant can be developed. All parameters in Eq. (1) can be determined. Therefore, the percentage foreign material content can be determined from the following equation:

$$\%\ Foreign\ material = -167.4509*\rho_{bulk} - 10.3571*\varepsilon' - 12.3778*\varepsilon'' + 0.9365*mc + 65.5941 \quad (5)$$

Predicted foreign material content for the training data set is shown in Figure 7. The predicted results with the training data set are in good agreement with the actual foreign material content. These preliminary results were obtained with *SEC* of 1.13% foreign-material content.

3.5. Artificial neural network

The predicted results with the training data set are shown in Figure 8. The predicted results were in good agreement with the actual foreign-material content. The *SEC* for foreign-material prediction was 1.03% foreign-material content, which was slightly lower than the 1.13% obtained by using the linear regression algorithm (Figure 7).

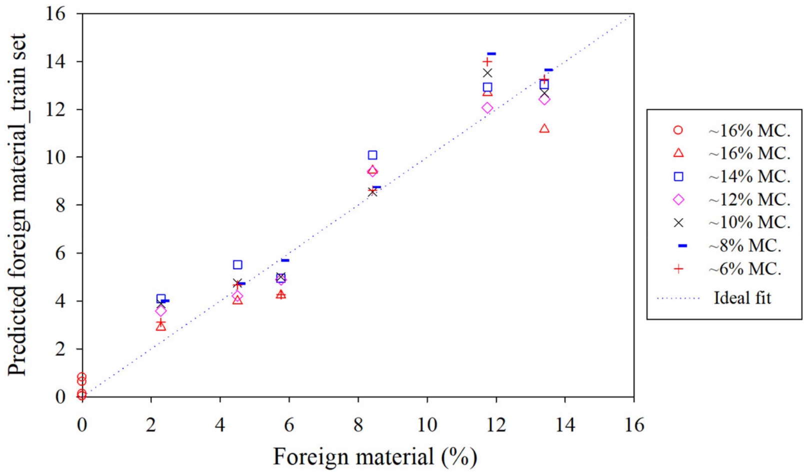

Figure 8. Prediction of foreign-material content with the training data set by using the artificial neural network algorithm at 10.0 GHz and room temperature (23 °C).

3.6. Algorithms validation

Figure 9 shows the predicted results of foreign material content with the validation data set at 10.0 GHz and room temperature (23 °C). The predicted results for foreign material content are shown along with the actual foreign materials for both algorithms. The artificial neural network algorithm was more accurate than the linear regression algorithm. The *SEP* for the artificial neural network algorithm was 1.36% foreign-material content while the *SEP* for the linear regression algorithm was 2.39% foreign-material content.

4. Conclusion

A foreign-material-content determination in uncleaned peanuts based on microwave measurements of dielectric properties and bulk density at 10 GHz and 23 °C was discussed. The dielectric properties of uncleaned peanuts (four-antenna system) and cleaned unshelled peanuts (nine-peanut-pods system) were measured by a microwave free-space measurement technique. This provides two groups of dielectric properties that are related to peanuts with and without foreign material parameters. The measured dielectric constant of uncleaned peanuts decreased with increasing percentage of foreign materials, while the dielectric loss factor remained constant. However, both dielectric constant and dielectric loss factor increased with moisture content. With the nine-peanut-pods measurement, only the moisture content was determined and used as a reference moisture content for cleaned unshelled peanuts. The bulk density of uncleaned peanuts was determined from the sample weight and volume in a container 12.1 cm × 21 cm × 20.5 cm. The bulk density decreased with increasing foreign material content. Moreover, moisture content and size of peanut pods influence the bulk density. All parameters, dielectric constant, dielectric loss factor, bulk density and moisture content were used to develop the foreign-material-determination

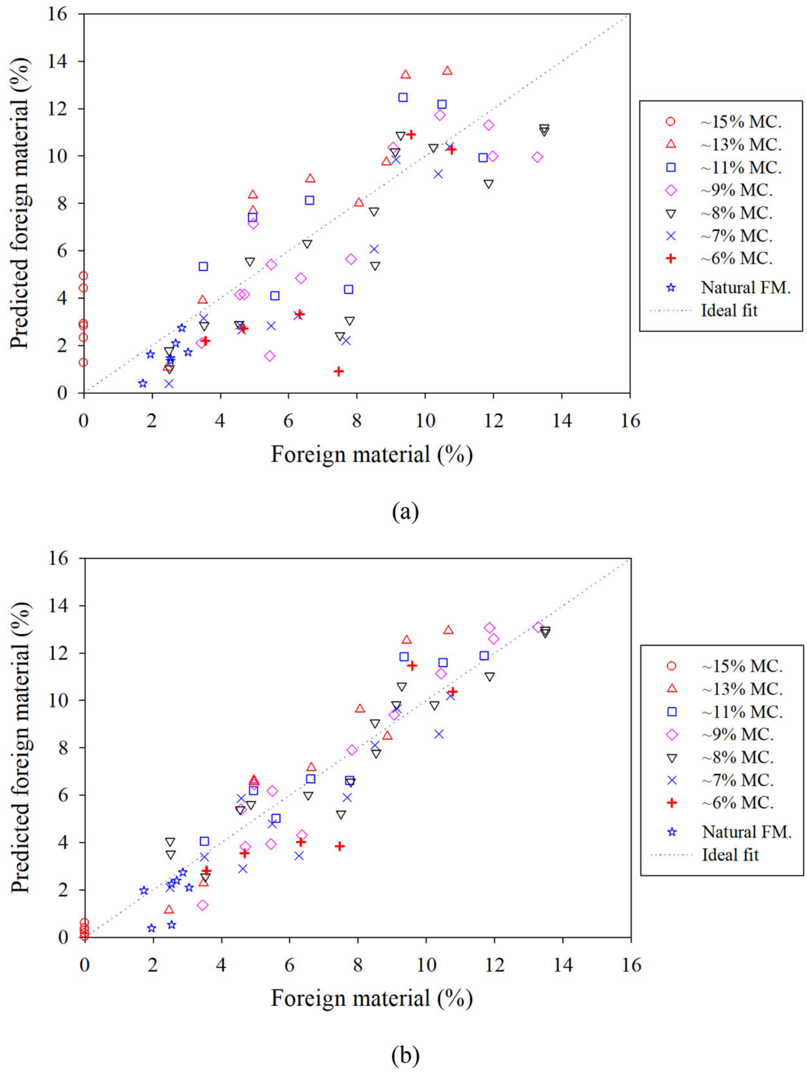

Figure 9. Prediction of foreign-material content with the validation data set at 10.0 GHz and room temperature (23 °C), (a) linear regression algorithm and (b) artificial neural network algorithm.

algorithms. Machine learning algorithms such as linear regression and artificial neural network were adapted for foreign-material determination. Foreign-material prediction for the prepared and natural unclean peanut samples with the artificial neural network (*SEP* = 1.36% foreign-material content) shows a better accuracy than the linear regression algorithm (*SEP* = 2.39% foreign-material content). The proposed measurement system is suitable for use in a benchtop instrument and provides rapid, nondestructive determination of foreign-material content and moisture content in uncleaned unshelled peanuts.

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