



Microwave Scanning Technology as a Non-destructive Testing Method for Detecting Black Heart in Potato

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

In recent decades, food scientists and engineers have attempted to develop an improve technologies that can detect the internal damages of agricultural produce under postharvest conditions using a various methods of destructive and non-destructive technologies. This study presents the technique of microwave scanning as a non-destructive technology for application in agriculture to detect black heart in potato tubers in a non-destructive way. A bi-static antenna configuration of microwave scanning setup operating at 2.45GHz was assembled, with a customized slotted rectangular microstrip antenna designed and simulated with CST, thereafter fabricate the antenna to be used as a microwave sensor in the setup, a miniVNA tiny double as a RF generator and S-parameter measurement was used to measured transmission coefficient (S_{21}) through samples of real potato, the analysis was based on the differences in the wave spectrum obtained between the good potato sample and the sample with black heart. The result obtained from the analysis of wave spectrum shows that there is a significant difference up to 5dB in the wave pattern of a good potato sample and the sample with internal damages. Accuracy up to 86% of true state of the tested sample was achieved using the technology. Hence, the method can be adequately used as a scientific way of grading and sorting a batch of potato non-destructively.

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1. INTRODUCTION

The idea of Non-Destructive Testing (NDT) is all about determining the existence of form of imperfections in bulk materials or assemblies of component without impairing the integrity or functionality of the inspected objects [1].

This non-destructive Testing (NDT) is not only needed in medical but also in industrial processes, geology, agriculture, security and other walks of life. For this purpose scientists and engineers have developed various tomography technologies that are applicable for each need in various fields of applications. Some of NDT technologies that have been explore for use in area of agricultural includes; Computerized Tomography (CT) that is based on gamma ray radiation [2], Magnetic Resonance Imaging (MRI) based on ultra-high magnetic fields [3], NMR based on the spins of atomic nuclei [4] Positron Emission Tomography (PET) based on nuclear particle radiation [5], ultrasonography that uses high frequency sound waves [6] and microwave imaging using microwave frequency [7] to mention few. But from all these mentioned non-invasive and non-destructive methods; microwave imaging (MWI) is quite well established and stands out, because it has the capability to be applied to different objects with minimal restrictions [8]. Non-invasive, non-ionizing, non-selective of conductive and non-conductive surfaces, fast to use and cost-effective of microwave imaging systems has made it a promising technology [9].

Microwave imaging can be defined as morphological studying of internal structure of an object by irradiating the object with low power Electromagnetic Wave at microwave frequencies [10]. Microwaves frequencies range from 300 MHz to 300 GHz range in the electromagnetic spectrum [11]. These Electromagnetic waves have some unique characteristics that make them suitable for subsurface sensing purposes. Characteristics such long wavelengths which make it to have ability to penetrate a wide variety of optically opaque and non-conducting materials of various composites such as ceramics, concrete, wood, foam, soil, biological tissues and ability to interact with their internal structure [12].

Potato (*Solanum tuberosum* L.) is the fourth most important food crop in the world after corn,

wheat, and rice [13]. One of the numerous hurdles in potato farming is the inability to preserve the quality of freshness of the produce to the end consumers. Causes of post-harvest losses of potato produce are many, the major ones is the quality deterioration attributed to physiological and mechanical damage to internal tissues (black heart) and combinations of several organisms action on the produce [13]. At present, the adopted method in use for detecting black heart and sorting in a batch of potatoes is solely based on conventional method of statistical sampling and manually destructive test process [14]. It's estimated that these destructive tests accounts for 0.5% of the post-harvest wastage volume, with a net value of more than £10 million annually [14] which represents a substantial economic loss yearly. This conventional method for the internal quality assessment of potato tubers is always laborious, costly, destructive and time-consuming, not only that; it is also subjective and inconsistent. As a means to reduce such wastage; technologies for non-destructive testing (NDT) of internal quality of potato tubers and classification with maximum safety have become important in recent decades.

Although, other possible technologies capable of NDT beneath a potato's surface exist, but they come with some issues that is limiting their usage such as; safety issues e.g. x-rays [15], operational or throughput limitations e.g. ultrasound [16], operational complexity of the system e.g. hyperspectral imaging [17] and high cost effective e.g. Near-infrared reflectance spectra (400-1200 nm) & visible laser [18] etc. But a better alternative is microwave imaging technique [19] due to its low cost, safety, high accuracy, versatile, compactness, non-contact and environmental friendly.

1.1 Concept of Microwave Imaging

The concept behind microwave imaging application for detecting internal structure of an object is based on the mapping of the electrical property distributions in the body when that body is subjected to microwave frequency. The difference in mapping (in the case of biological tissues) of affected/bad tissue from good tissue is based on the difference in tissues dielectric properties which depend on content of water within the tissues [20]. The increases of water content equate an increase in values of dielectric constants and the conductivity and verse versa.

The dielectric properties of biological materials indicate how much microwave energy is absorbed, transmitted and reflected during interaction between the tissues and electromagnetic energy. It has been established that microwave spectrum of defected tissues changes significantly when compared to the microwave spectrum of normal tissue [21].

These properties can be defined in terms of the complex relative permittivity, $\epsilon = \epsilon' - j \epsilon''$, where the real part ϵ' is known as the dielectric constant, and it is associated with energy storage in the electric field in the material while the imaginary part ϵ'' is called dielectric loss factor, and it is associated with the energy lost or the energy converted to heat in the material during the process of irradiation.

Several computer models have been developed to investigate the interaction of E.M waves and biological tissues. Debye and Cole-Cole models are the most commonly used models. The Debye model simulates the frequency dependence of DPs of tissues sufficiently [22, 23].

Active microwave imaging is been carried out by transmitting a sequence of electromagnetic waves through the transmitting antenna to the object to be image and measuring the scattered electromagnetic field at the perimeter of the object through the receiving antenna, these signals are characterized by scattering parameters (S-parameters) taking from the measuring equipment called Vector Network Analyzer (VNA). The VNA measures the parameters as S_{nn} and S_{nm} . Where, S_{nn} refers to the ratio of reflected signal at port n to the incident signal at port n while S_{nm} refers to the ratio of transmitted signal measured at port n to the incident signal at port m. When these parameters are plotted in a graph; it is called reflection coefficient (S_{11}) and transmission coefficient (S_{21}) spectrum.

S_{11} is the forward reflection coefficient, where input return loss, input match and voltage standing wave ratio parameters were expressed.

S_{12} is the forward transmission coefficient, where the gain and loss in the network were expressed.

Therefore, the analysis of the results of this experiment is based on the differences in S_{12} obtained during the data collection.

Few of bulk of related work reported in literature that used different techniques to determine the internal defects in potato are briefly review. Jivanuwong S. [6] used ultrasonic sound technique; the author was capable of detecting hollow heart cavities greater than 0.5 cm³, an accuracy of 98% was recorded by using a lower frequency (50 kHz).

Other researchers; Angel D. et. al [17] presents a good method to detect the presence of the hollow heart, an internal disorder of the potato tubers, using hyperspectral imaging technology in the infrared region. The results obtained show that hyperspectral imaging technology was able to achieve an accuracy of 89.1% of correct classification.

A transmission spectrum system in the visible/near infrared (Vis/NIR) region of 513–850nm was developed by Zhu Z. [24] to determined blackheart in potatoes. Principal Component Analysis (PCA) was used to select sensitive wavelengths; and Partial Least Squares-Linear Discriminant Analysis (PLS-LDA) was used to develop classification models. The analysis of the results showed that the overall classification rate by PLS-LDA method decreased from 97.11% to 96.82% in calibration set and from 97.11% to 96.53% in validation set, which was acceptable to classify blackheart potato from normal ones.

Publication presented by Mohammed I. [14] was a first investigation into the use of microwaves imaging method for the non-destructive testing to determine the presence of blackheart cavities in potato. The author simulates a spherical potato with and without a cavity using CST. Simulations results show that; changes to how microwaves propagate through a potato caused by a cavity can produce measurable changes in transmission coefficient S_{21} at the potato's surface of up to 26 dB. Also, lab-based readings of the change in S_{21} caused by a phantom cavity submerged in a potato phantom liquid confirms the results of the simulation but with much reduction in S_{21} power obtain in the order of 0.1 dB.

1.2 Dielectric Properties of Potatoes

As reported in [14] that due to the high water content of the potato; normal potato tissue has a high value of D.P while the defected/damaged tissue have a lower D.P value compare to the normal; this difference D.P can be detected when

these tissues are subjected to E.M waves interaction. This is the theory that this research work is anchor on.

2. MATERIALS AND METHODS

Materials used to carry out this research work are; raw samples of sweet potato (*Ipomoea batatas*), Vector Network Analyzer (miniVNA tiny), Personal Computer (PC) our customize microwave antenna, R.F amplifier.

2.1 Assembling of Microwave Scanning System

The architecture and different component of our scanning system are depicted in Fig. 1.

The microwave scanning system adopted in this work was established in [25], [26], the system operates on the microwave radar image acquisition principle, it consists of a bi-static antenna configuration, the VNA used (mini VNA tiny; 1- 3GHz, @ 10Hz steps, -6dBm o/p power, Dual ports with S_{11} and S_{21}) serves as a RF signal source and S-parameter measurement equipment, a microstrip antenna used for transmitting and receiving RF signals were connected to the respective port, but the receiving antenna is couple to the VNA with wide band microwave amplifier (6-12DCVolt, 0.1-2000MHz, +10dBm(10mW)) to boost the received signal in order to have a substantiate

amount of received power due to inbuilt power level of VNA used. The whole system is connected to PC (CPU: 2.6GHz Intel Core i7-9750H, RAM: 16GB, Storage: 512GB SSD, Display: 17.3-inch Full HD (1920 x 1080), GPU: 4GB NVIDIA GTX 1650) through VNA which serves as the host computer that contain the software used for analyze the result gotten and data storage.

For the practical assembling of the microwave scanning setup, our customized slotted rectangular microstrip antenna designed and fabricated for this purpose was used as a microwave sensor, these antennas were mounted upon brackets, one for transmitting and other for receiving, both vertically facing each other. To ensure that the setup is free from any near field effects, the antenna's separation distance is determined by the formula $r = \frac{2D^2}{\lambda}$ Where, D is the maximum linear dimension of the antenna λ is the operating wavelength. With a frequency of 2.45 GHz and maximum dimension of our antenna is 10.2 cm, a far field distance is calculated as $r = \frac{2 \times (10.2)^2}{2.22} = 1.99 \approx 2\text{cm}$. Marked A4 paper was placed under the antennas to ensure far field position is maintained, and also to ensure that the antennas remain properly aligned, the whole setup was arranged on a laboratory table.

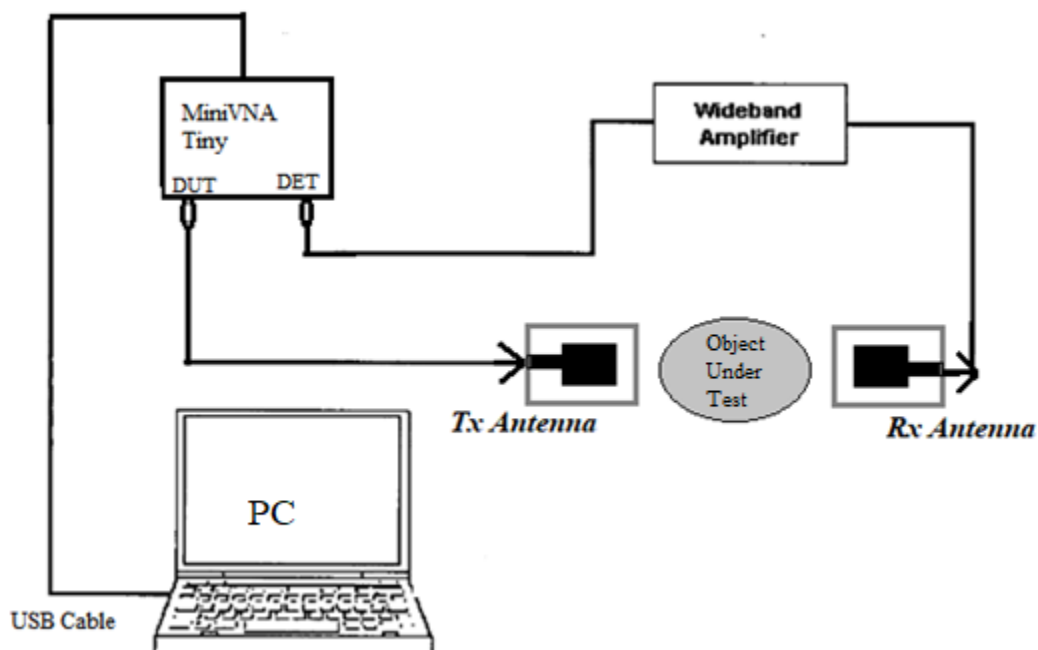


Fig. 1. Block diagram of scanning system

The two main electronics component in the setup (wide band RF Amplifier and mini VNA) were powered by computer through respective USB cable connected to serial ports of PC, the scanning operation and data recording were completely handle by the laptop.

2.2 Sample Acquisition and Preparation

Samples of potato provided for this experiment were sought for from potato market, some were bought from fresh potato market; while some were bought from store market with believes that some of them have stayed long in the store to have developed an internal damages. All these samples were cleaned from dust and clay by washing them in a tap water then spread them on a laboratory table to be dried by air; and for experimental purposes in order to match with our antenna and setup size, moderate sizes of these potatoes were selected.

There are two sets of samples prepared for this experimental measurement; the first set is the sample with artificial black cavity, this cavity was created in a sample of potato by making a groove in form of cone shape in such a way that the cone shape that was removes can be fixed back into its place neatly, from this groove a hole is created inside the potato, this hole is filled up with dry matter of rotten potato tissue as shown in Fig. 2.

Second set of sample were prepared by getting some numbers of potato from store that were assumed to comprises of good and bad potatoes; label them as sample 1, 2, ...12 appropriately. But one fresh and very good sample was intentionally selected and label as sample C to serve as a control sample in which other samples will be making reference to as shown in Fig. 3.



Fig. 2. Creating artificial potato black heart



Fig. 3. Labeled samples



Fig. 4. Process of Scanning the potato samples

2.3 Measurement Procedure

The system operational software was pre-set and calibrated to its standard and specification before taken the first measurement with empty space in-between the antennas; the system was again fine tune to be double sure that the antennas are in alignment and also they are in far field before recorded the reading as a baseline. Then, for each set of sample scanning; the sample was placed at mid-point between the two antennas far field region, with the VNA fully set in a transmission mode, the system was given command from PC to scan the sample over the set frequency range of 1–3 GHz and a pre-set scanning period of 3 μ s for deep scanning, the resulting transmission coefficient spectrum (S_{21}) was recorded using the miniVNA software (vnaj 3.4.6) already install in PC.

From the first set of samples prepared; a measurements were taken when the sample is intact, when hole is created in it through the cone cut-out and when the hole is filled up with dry black matter of dead potato tissues that was used as artificial black heart; S_{21} spectrum for each case of measurement was carefully recorded.

Again from second batch of prepared samples; the sample earmarks as control sample was scanned first; before all the other selected

samples were scanned one after the other, the S_{21} spectrum of the control sample was recorded as a baseline spectral curve to be used as a reference curve to compare with other samples S_{21} spectral curves. Raw data of the spectrum display were collected and plot in excel Microsoft for easy comparison. Activities of the measurement were shown in figure 4. After measurement, the samples in second batch were sliced to open them and physically see the true state of their internal structure.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Results for Artificial Black Heart Scanning

The S_{21} spectrum that was obtain when the signal was transmitted through an empty space between the antennas, through fresh intact potato, when the hole was created in it and when the hole was filled with artificial black heart are shown in figure 5. It was observed that at 2.45GHz; the peak value of S_{21} in empty space is 19.5dB which is expected because the maximum power is been transferred, the value of potato with hole is 16dB, the value for intact potato is 10dB; while 5dB is correspond to potato with hole filled with artificial black heart.

From the graph; it is observed that there is a substantial difference among these curves especially around our working frequency (2.45GHz). This difference in the spectrum indicates that (by theory) there is difference in the dielectric value in the tissue of the same material subjected to the same electromagnetic radiation under the same condition; and this difference in the dielectric value means there is a morphological changes inside the tissue which can mostly be termed as tissue defect or black heart of potato in our case. These differences are good enough to proof that microwave imaging can be used to detect internal defects in potato non-destructively.

3.2 Results for Random Scanning

The S_{21} graph obtained for a series of potato samples scanned at random is shown in Fig. 6, it

can be seen from the graph that some of the graph are closely follows the same pattern; while some shows little difference and some large difference.

Most of the spectrum that follows almost the same pattern indicates that there is little or insignificant variation in the dielectric value of those samples, while those that has a substantial difference shows that there is a noticeable variation in the dielectric values, when all the samples were slice open as shown in Fig. 7 to physically inspect the state of their internal conditions, the reason for such deviation was confirmed; the internal tissue of those samples with such differences were defected which can be physically seen, and it is the cause for the changes in dielectric value that affects the propagation of wave through it.

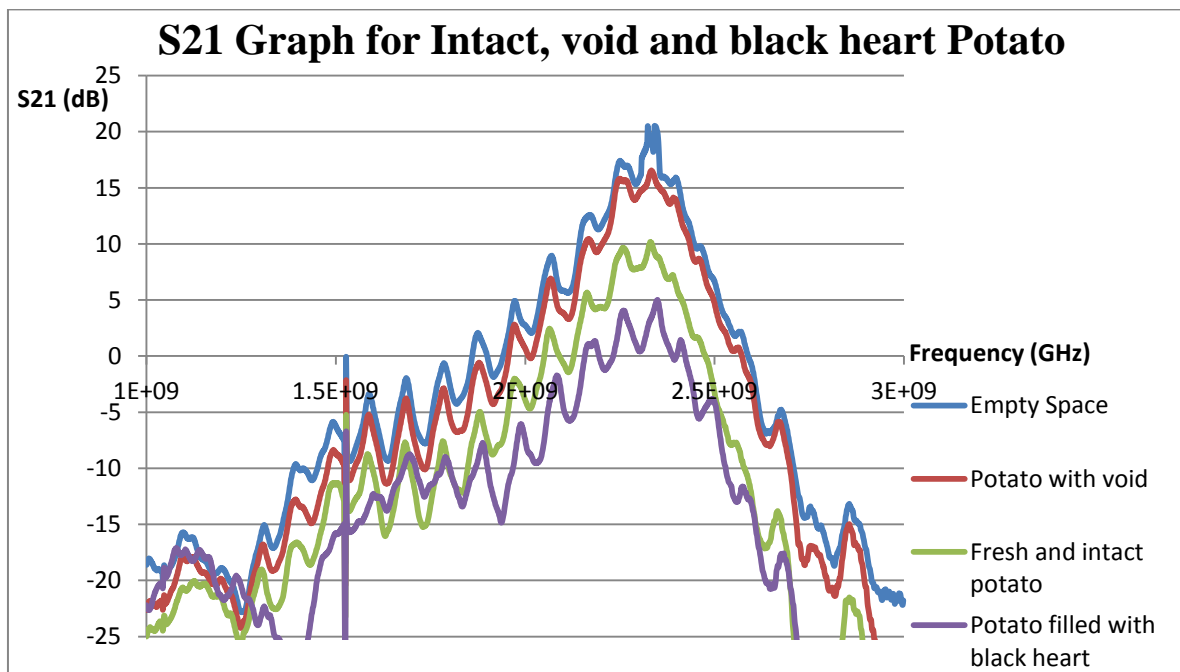


Fig. 5. S_{21} Graph for void, intact and artificial black heart potato

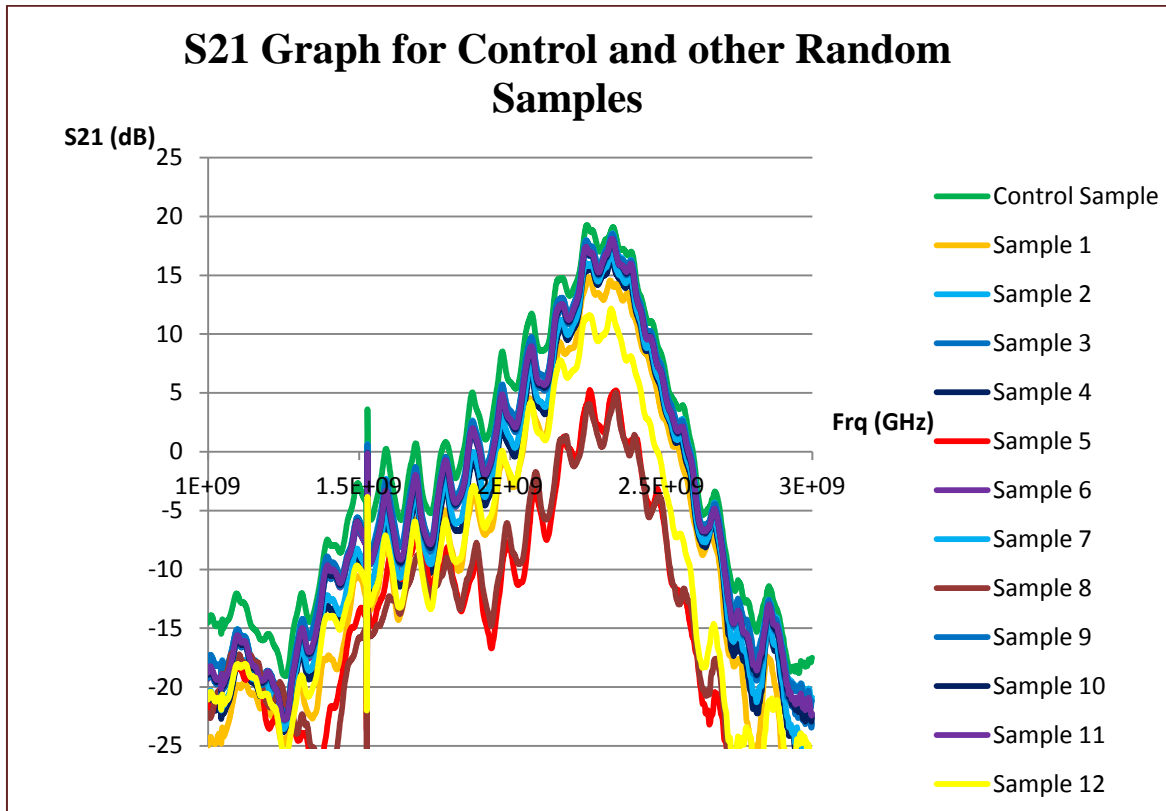
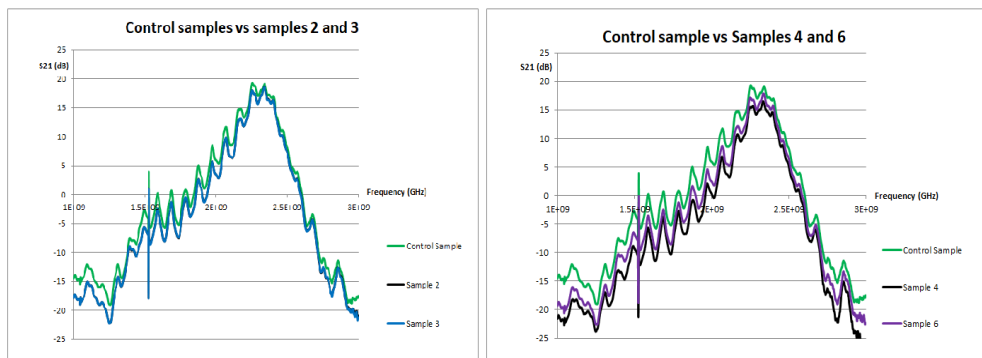


Fig. 6. S₂₁ Graph of random scanning of potato samples



Fig. 7. Physical inspection of potato inside



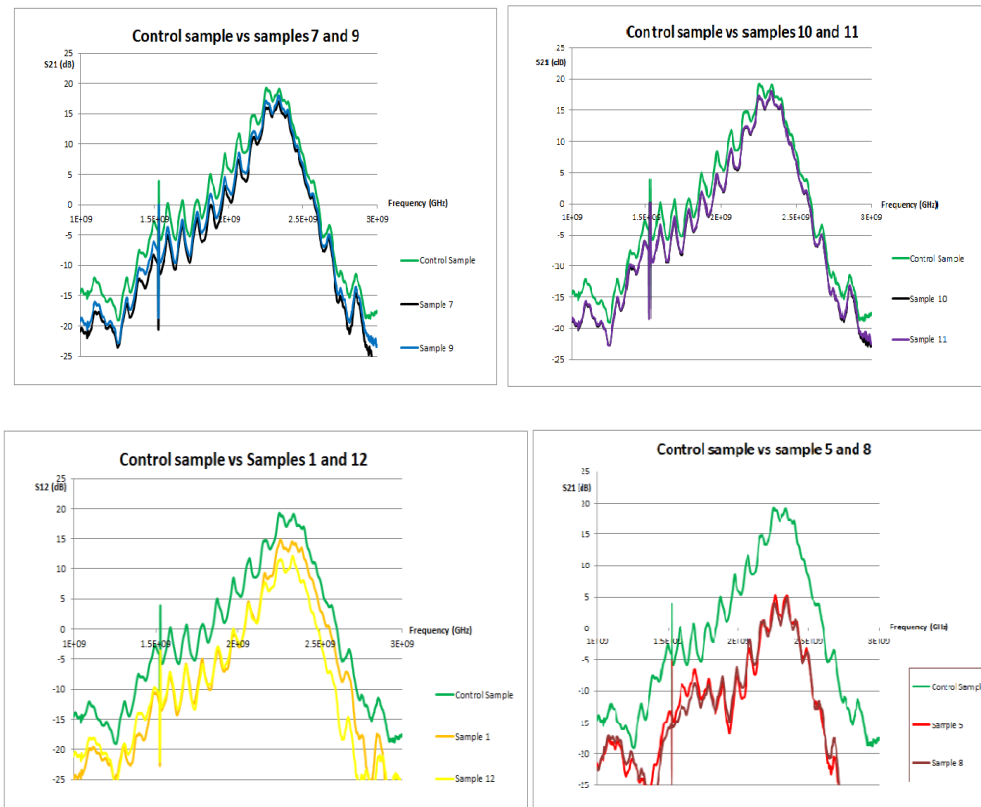


Fig. 8. S_{21} Graphs of control sample vs other samples

The Fig. 8 below is the breakdown of fig. 6, it shows S_{21} graphs of control sample and other samples when comparing them to see how much different each is from the reference point. It is seen that samples 2, 3, 4, 6, 7, 9, 10 and 11 show no much difference in the spectrum pattern from control sample which indicate that theoretically they have the same dielectric value, and also physical examination of internal structure from Fig. 7 confirm that those samples are good. Again, looking at the graph of control sample and samples 1 and 12, it can be seen that the peak difference at 2.45GHz is 4dB and 6dB respectively which indicated that; there is a difference in dielectric value of those samples that causes the differences, a close look at the picture from Fig. 7 shows that sample 1 has started changing its natural color from edge towards the center while rotten have set in from edge of sample 12. From the graph; the value of the differences indicates the level of the internal damage, it can therefore be confirmed from picture and the graph that; samples 1 and 12 are classified as in between good or bad depending on the set standard from grading or better still acceptable. In the same vein, when looks at the graph of control sample and samples 5 and 8, a

wide difference can be clearly seen which indicate the differences in dielectric values of those samples, theoretically wave propagation through them will not be the same, S_{21} value is high when D.P is high and vice versa. Physically inspection from picture in Fig. 7 shows that the internal tissue of samples 5 and 8 have gone bad, from the scanned graph; samples 5 and 8 are classified as bad.

Our result is perfectly in agreement with the result got in [13] which is when the reading were taken from two opposite antenna; that there is a substantial reduction in the transmitted S_{21} value when there is a void/black heart as compared to when there is none.

The result obtained from this experimental work of using real potato is perfectly in agreement with the results got in similar works consulted as a base article reviewed for this research work. Mohammed et.al [14] demonstrated same method by simulation and with potato phantom, and it was concluded that; the reading taken from the antennas surrounded the potato phantom; the two directly opposite antennas to the signal source recorded a substantial reduction in the

transmitted S_{21} value when there is a void/black heart in potato as compared to when there is none. In the same vein, Zhu et.al [27] used visible/near infrared (Vis/NIR) transmission spectroscopic technique in the 513–850 nm region, they concluded that there is a significant reduction of 0.58% in the transmitted signals across sample of good compared to bad potatoes. Thus, this research work is validated with existing result of similar research work. This method is superior to others because of its non-selective of conductive and non-conduct materials, not limited by whether (night and day) and the simplicity in usage. Accuracy up to 86% of true state of the tested sample was achieved using the technology.

4. CONCLUSION

This experimental work clearly shown that; the transmission of electromagnetic waves through an object is affected by the difference in dielectric properties (presence/absence or high/low of a dielectric value) of the object. Also it has been demonstrated that the differences in the dielectric properties inside the object under test can be detected from outside by measuring the response of the transmitted parameters (S_{21}), and by examining the transmitted waveform spectrum; the level of differences in the dielectric could be determined. This finding is a pathfinder to develop an instrument capable of detecting in large-scale black cavity in potato and other tubers that is simple in construction, low in cost with less complexity; it requires only a simple comparison routine rather than a complete tomographic reconstruction, the system can be further developed to an automated system that can be used to measure the tuber and display the actual state of the internal tissue as either good or bad.

5. RECOMMENDATION

Though this work confirm the establish theory of using microwave scanning for NDT in agricultural produce, there are areas for further investigation and improvements which includes; Other than establishing the concept of this theory, designing of a more stable system that incorporates a generic algorithm and/or machine language to classify and identify the desire flaws in the object under test is essential and the consistency of the experiment should be validated on different variety of potato.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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