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Alternatives for PCB Laminates: Dielectric Properties' Measurements at Microwave Frequencies

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Additional information is available at the end of the chapter

1. Introduction

1.1. Objective

To determine dielectric properties of paddy waste as a potential alternative material for conventional PCB laminate materials. Paddy waste residues, which already possess the characteristic of these conventional laminates, can be strengthened by fabricating it in a tightly-compacted, highly-dense package. These PCB laminates need to be insulated to avoid short circuit, and be physically rigid to mechanically provide stability for the placement of the copper. These properties will then enable a low-cost, sustainable, and renewable solution, with a comparable performance to PCB laminates available in the market.

1.2. Background history

Perlis is the smallest state in Malaysia with agriculture as its main economic activity. Rich rice fields cover most part of the state, enabling easy access to paddy wastes for the fabrication of these particle boards. The raw materials used in this work are rice husk and rice straw, gathered after the harvest season. It is known that fibers with the smallest particle size exhibits the highest tensile strength and hardness [1], hence its increased usage and demand. Within the 2010-2011 period only, about 577 million tonnes of rice (*Oryzae Sativa*) was produced worldwide. Malaysia is one of the more than 80 countries contributing to this sum, with 100,000 tonnes produced annually. Relative to the large quantity of produced agricultural residues (rice husk and rice straw), only a minor portion is reserved as animal feed, while the rest are burnt openly, causing concerns of air pollution [2]. Various

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other suitable application for such residues are such as mat production, pedestrian bridge, microwave electronic design application, etc [3-4].

Dielectric properties of a material define the physical-chemical properties related to the storage and loss of energy contained in a material or substance. The knowledge of a material's dielectric property is necessary in determining its suitability for a specific application. This property, which includes complex permittivity and dissipation factor, is unique for every material type. These unique sets of electrical characteristics are dependent on electromagnetic properties of the materials. Measurement of dielectric properties involves measurement of the complex relative permittivity (ε_r) and complex relative permeability (μ_r). A complex relative permittivity (ε_r) consists of a real part and an imaginary part. The real part of the complex permittivity, also known as dielectric constant is a measure of the amount of energy from an external electrical field stored in the material. The imaginary part is zero for lossless materials and is also known as loss factor. It is a measure of the amount of energy loss from the material due to an external electric field. The term tangent loss (tan δ) represents the ratio of the imaginary part to the real part of the complex permittivity, and is also known as loss tangent, dissipation factor or loss factor. Accurate measurements of these properties enable scientists and engineers to incorporate the material for the suitable application, for more solid designs or to monitor a manufacturing process for improved quality control [5].

2. Permittivity and tangent loss definitions

The dielectric properties are, by definition, a measure of the polarizability of a material when subjected to an electric field. To evaluate materials, the dielectric properties are represented by the relative complex permittivity, $\varepsilon_r = \varepsilon' - j\varepsilon''$, where ε' is the dielectric constant which describes the ability of the material to store energy, ε'', on the other hand, is the dielectric loss factor, which reflects the ability of a material to dissipate the electric-field energy.

Permittivity (Dielectric Constant)

$$K = \frac{\varepsilon}{\varepsilon_0} = \varepsilon_r = \varepsilon'_r - j\varepsilon''_r \tag{1}$$

ε_0 = is the free space of permittivity interaction of a material in the presence of an external electric field.

Permittivity (ε), also known as the dielectric constant, describes the interaction of a material with an electric field. Dielectric constant (k) is equivalent to the relative permittivity (ε_r) or the absolute permittivity (ε), relative to the permittivity of free space (ε_0). The real part of permittivity (ε'_r) is a measure of how much energy from an external electric field is stored in a material. The imaginary part of permittivity ($j\varepsilon''_r$) is called the loss factor and is a measure of how dissipative or loss of a material is to an external electric field.

Loss Tangent

When complex permittivity is drawn as a simple vector, the real and imaginary components are 90^0 out of phase. The vector sum forms an angle, δ, with the real axis (ε_r'). The relative "loss" of a material is the ratio of the energy lost to the energy stored.

$$\tan \delta \frac{\varepsilon_r^{''}}{\varepsilon_r^{'}} \tag{2}$$

$$\tan \delta = D = \frac{1}{Q} = \frac{\text{Energy Lost per cycle}}{\text{Energy Stored per cycle}} \tag{3}$$

In some cases the term "quality factor or Q – factor" with respect to an electronic microwave material is used.

Agricultural residues have been subjected to increasing interest, study, and utilization for some decades. The increase in environmental concerns rationalizes, the reduction of polymers' usage, not only because of their non-biodegradability, but also due to energy-intensive production. In other words, polymer production and processing requires large amounts of oil as raw material, which is notoriously not renewable. All these issues induce the need for alternatives.

Paddy residues such as rice husk and rice straw, shown in Figure 1, are materials of interest for a wide range of applications. Non-destructive dielectric properties' measurements are essential for proper understanding of their electrical behavior, ensuring that they could be effectively put into applications. The use of paddy residues is advantageous due to its high silica content and thick walled , providing a fire-resistant feature. For a typical paddy waste fiber, burning causes a layer of char to develop on the outer surface, insulating its inner straw [6].

| (a) | (b) |

Figure 1. Paddy residues (a) rice straw (b) rice husk

At radio and microwave frequencies, dielectric properties of paddy waste materials are dependent on frequency, moisture content, and temperature. In fact, at these frequencies, water is the most influential factor due to its polar nature. The effect of temperature is also water-related, where the change in temperature affects the energy state of water molecules, hence influences their aptitude to follow the alternating electric field [6]. Since water inside the paddy plant is bound to the inner structure, the dielectric properties' frequency dependence is not as spectacular as that of liquid water. Samples of agricultural waste products, rice husk and rice straw, of different resin moisture contents were prepared by pouring Urea Formaldehyde (UF) or Phenol Formaldehyde (PF) paddy samples to bring them to the desired moisture level [8]. Measurements at high frequencies are often taken using two different measurement techniques with different degrees of accuracy, given the granular nature of the proposed materials.

At microwave frequencies, various techniques have been developed to determine these complex properties ranging from time-domain or frequency-domain techniques, utilizing one port or two ports, etc. Every technique has its own limitation, either to a specific range of frequencies, materials or applications. Several popular measurement techniques are the transmission line techniques (waveguide, coaxial and free-space), impedance, dielectric probe and cavity methods [1-8]. Amongst these techniques, free-space measurements and high temperature dielectric probe techniques are chosen based on their suitability for paddy waste dielectric properties measurement. Both setups are shown in Figure 2. The free space measurement technique allows reflection and transmission measurements without direct sample contact. On the contrary, the dielectric probe technique is performed by contacting or immersing the probe into the sample. Both techniques do not require any special fixtures or containers, and they are best applied for thin, flat, parallel-faced materials, or other materials which can be formed into this shape. These measurement techniques are non-destructive and can be gathered in real time, allowing them to be used in process analytic technologies.

For the free space measurement system, a pair of horn antennas providing plane waves at a defined distance, are placed at either ends of a material under test (MUT), as shown in Figure 2. Minimal sample preparation is required [9-11]. The sample thickness is selected to ensure at least 10 dB one way attenuation and the time domain gating feature of the PNA is utilized to ensure an accurate measurement. The permittivity of a material's sample can be calculated automatically using the Agilent 85071 E software, with the signals transmitting and reflecting from the sample. The width and height of the sample (perpendicular to the wave propagation direction) must sufficiently be larger than the horn antennas to avoid inaccuracy caused by signal diffraction at sample edges.

Figure 2(a) shows the High Temperature Probe measurement procedure, which is done by contacting the probe to a flat surface of a solid, or immersing it into a liquid or semisolid. The fields at the probe end "fringe" into the material and change as they come into contact with the MUT. The reflected signal (S_{11}) can be measured, and then related to ε_r. On the other hand, Figure 2(b) shows the free space measurement technique, based on the reflection coefficient (S_{11}), transmission coefficient (S_{21}), or both. The popular "S-parameter" approach (Nicolson-Ross or Weir) uses both S_{11} and S_{21} to calculate both ε_r and μ_r where S_{11} and S_{21} are

composed of multiple-reflections from both boundaries. The sample must be thick enough to contain the wavelength, ℓ of interest in order to be measurable, ideally 180°, or ½ ℓ. At mm-wave frequencies, samples thicker than 1 ℓ can create multiple root errors. The sample must be far enough, away from the antenna to be out of the reactive region, ideally at least $2d^2/\ell$, where d is the largest dimension of the antenna.
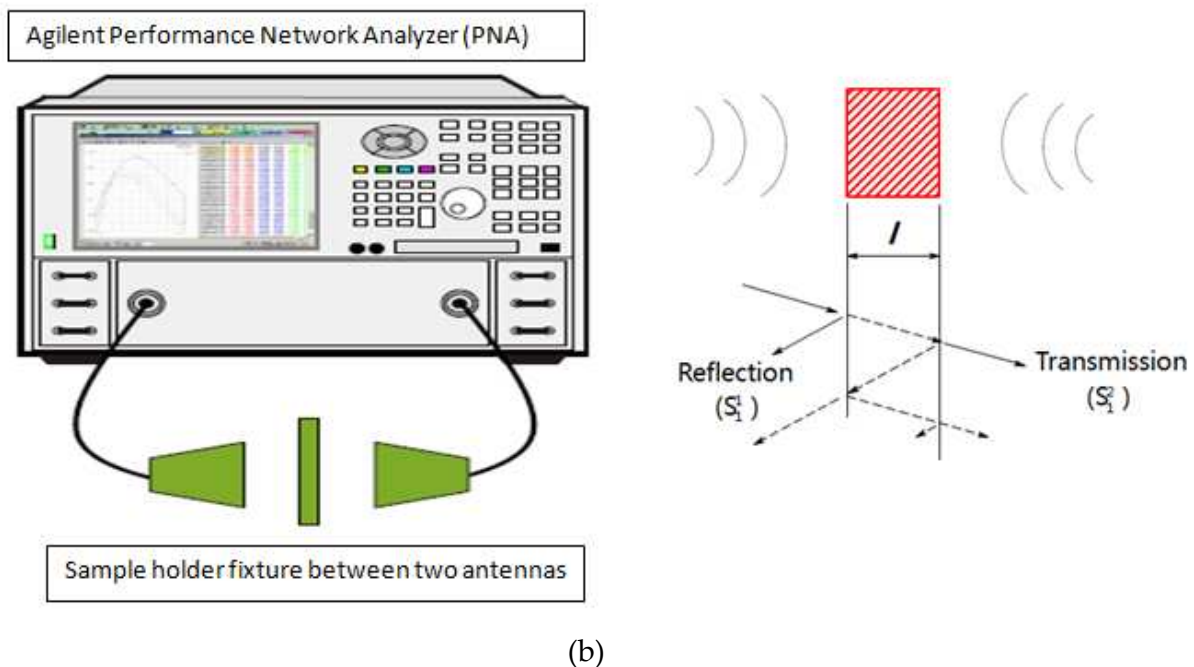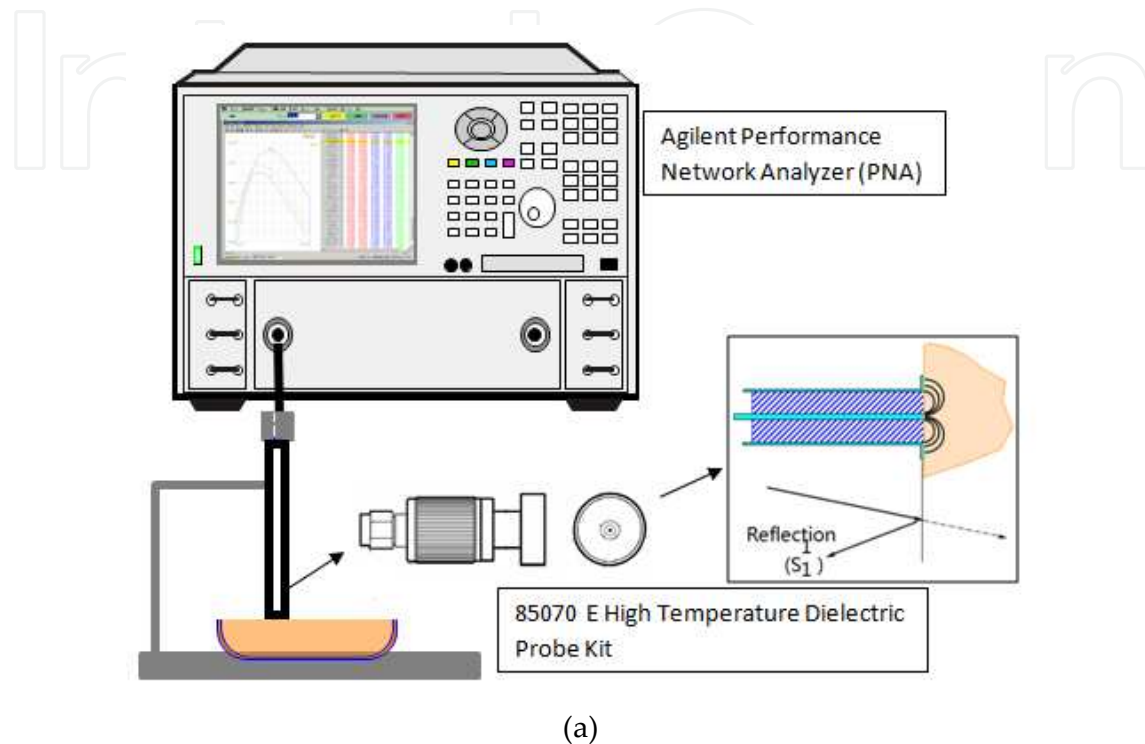

(a)

(b)

Figure 2. Measurement techniques for paddy waste (a) High Temperature Dielectric Probe Technique (b) Free Space Measurement Technique.

A microwave laminate is a dielectric material which is usually a poor electrical conductor, commonly used as an insulating layer in building PCBs. Porcelain, mica, glass, plastics and some metal oxides are several examples of these dielectrics. The lower the dielectric loss (proportion of energy lost as heat), the more effective the dielectric material is. If the voltage across a dielectric material becomes too large, and intensifying its electrostatic fields, the material will begin current conduction. Examples of popular PCB laminates are shown in Figure 3, i.e Rogers 5880, Rogers 4350, FR-4, Taconic TLY-5 and etc.
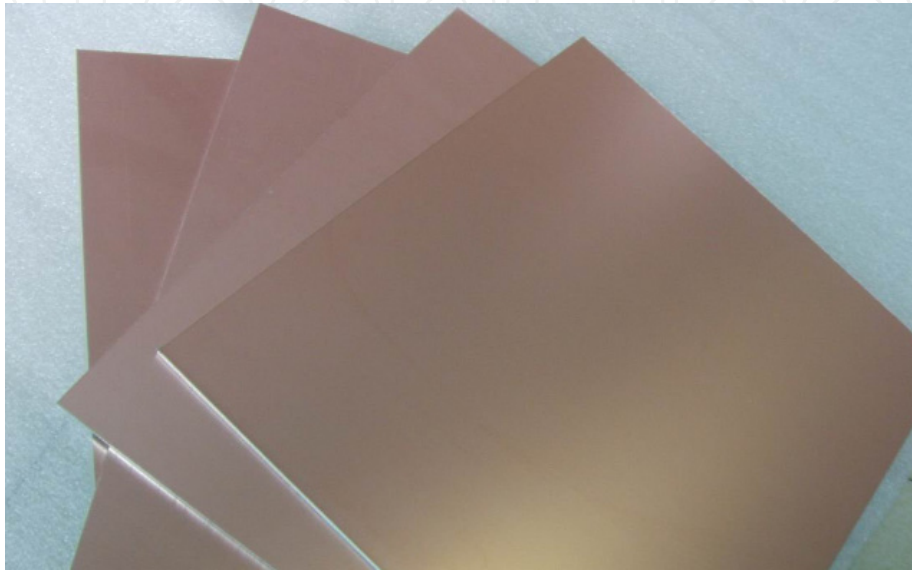

Figure 3. Existing of PCB laminates in the market.

This investigation intends to analyze the dielectric properties of two major paddy waste commodities, i.e., rice husk and rice straw, with each of them representing significant structural and compositional differences. Dielectric properties of paddy wastes are measured using Free Space Measurement Technique and High Temperature Dielectric Probe Kit over a range of microwave frequencies, at room temperature. This is potentially interesting for the microwave industry, as a comparison with the commercially available PCB laminates in the market is also carried out.

Body:

- Problem Statement

This work chooses paddy waste materials due to the sustainable practice of using natural by-products due to the rising environmental concern. About one million tones of these residues are produced over the entire 200,000 hectare per season in Perlis. Thus, besides being available abundantly, its usage avoids open burning activity, which is its common disposal method [6]. This activity obviously deteriorates air quality and raises health risks. With the ban of open burning, beneficial and sustainable alternative methods of such agricultural waste disposal are required. Moreover, the materials for commercial PCB laminates are costly and less environmental-friendly due to the usage of chemicals. The total chemical compounds used in the paddy waste particle boards production, In this case, there

is only 9.3 % of the total amount of material used. Thus, characterization of these paddy waste particle boards will be necessary for it to be proposed as an alternative PCB laminate which is low-cost and sustainable.

- Method used

The project is summarized into three major phases, consisting:

Phase 1: raw paddy wastes collection
Phase 2: particle board fabrication,
Phase 3: dielectric properties measurement
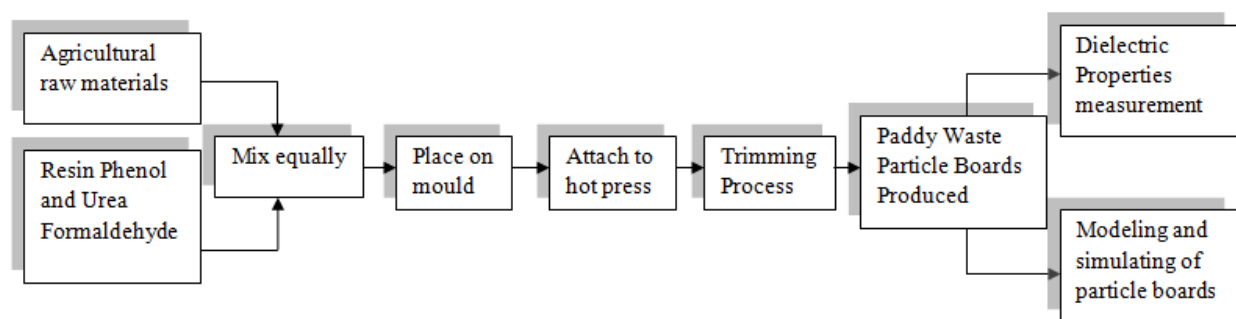
Fabrication of paddy waste particle boards

Figure 4. Step of analyzing paddy wastes

The paddy wastes, i.e. rice husk and rice straw, are compressed into a solid board for dielectric measurements, using different percentages of Urea Formaldehyde (UF) and Phenol Formaldehyde (PF) resins. Both are important components in determining its dielectric property. Figure 4 summarizes the rice husk and rice straw particle boards fabrication process. The paddy wastes are first collected from the rice fields before being transformed into particles boards. The boards' dielectric properties are then determined using the Free Space Measurement Technique (FSM) and High Temperature Dielectric Probe Technique.

- Paddy waste raw materials

Figure 5 shows the types of paddy waste raw material which has been used for fabrication.

- Fabrication of Paddy Waste Particle Boards

Firstly, two different bonding agents, Urea Formaldehyde (UF) and Phenol Formaldehyde (PF) are mixed with the respective paddy waste in a basin. UF, also known as urea-methanal - named so for its common synthesis pathway and overall structure - is made from urea and formaldehyde. It possesses a high tensile strength, low water absorption, and high surface hardness. On the other hand, PF is the result of an elimination reaction of phenol with formaldehyde. It is formed by a step-growth polymerization reaction which may be either acid- or base-catalyzed. Figure 6 shows the two types of resin which is important in providing the moisture content in the paddy waste boards, and directly affecting their dielectric properties

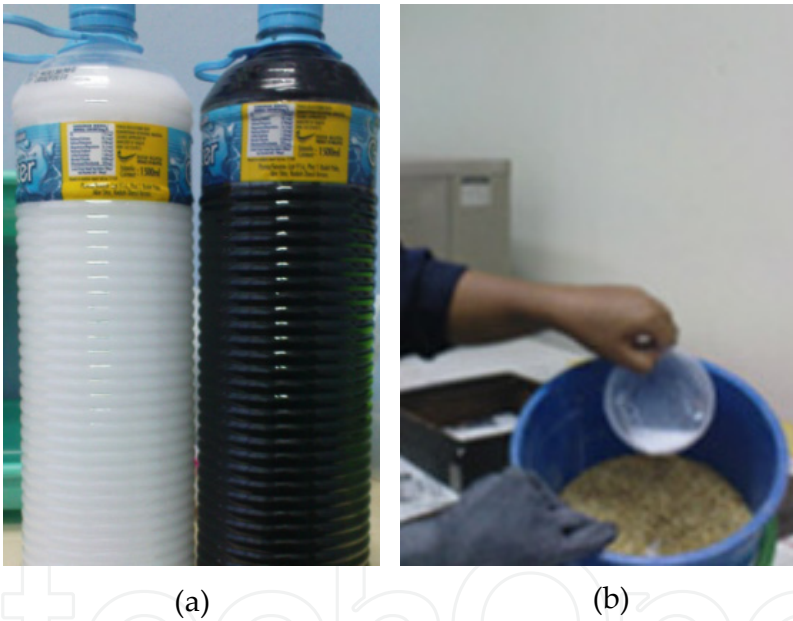**Figure 5.** Paddy waste materials (a) rice husk (b) rice straw

Figure 6. (a) Urea Formaldehyde and Phenol Formaldehyde resins (b) resin -paddy waste mixture

Paddy Wastes	Resin, Percentage, %	
	Urea Formaldehyde	Phenol Formaldehyde
Rice Husk	10	10
	20	20
	30	30
Rice Straw	10	10
	20	20
	30	30

Table 1. Rice husk and rice straw resin percentage fabrication matrix.
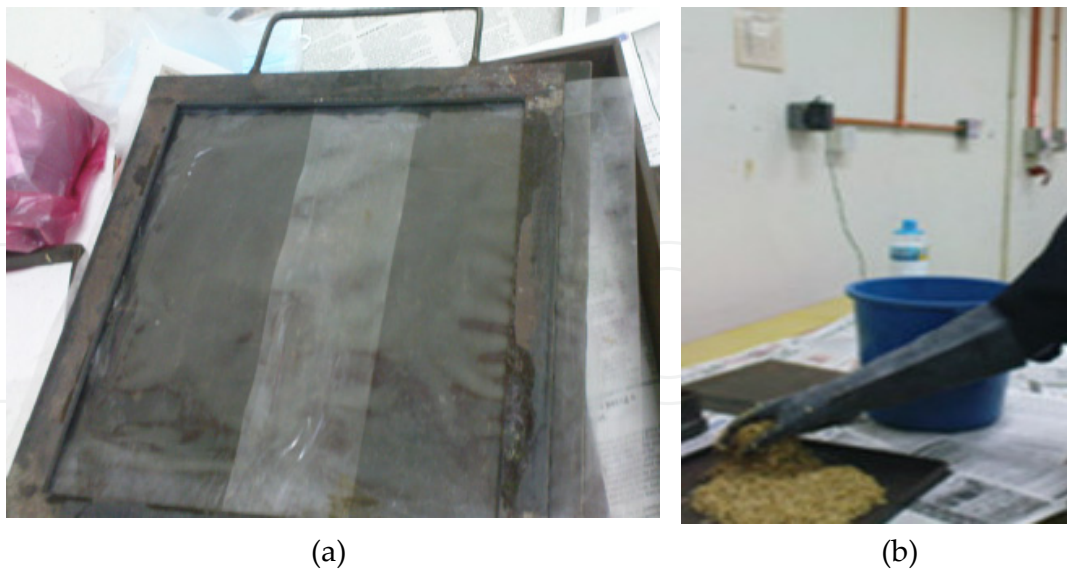
<div align="center">(a)   (b)</div>

Figure 7. (a) Rectangular-shaped mould (b) paddy wastes-resin mixture transfer into the mould

First, 500 g of rice husk is weighed and mixed using three different UF resin compositions: 10%, 20% and 30%. This process and procedure is also repeated for rice straw. Another set of similarly composed mixture using UF, rice husk and rice straw is also prepared. Figure 6(b) shows the resins-paddy wastes mixing procedure, while Table 1 presents the fabrication matrix. The mixed material is then placed into a rectangular, 245 x 245 mm mould shown in Figure 7. This mould is chosen to enable the fabrication of a larger particle board for use in the free space measurement technique.

Next, the mixture placed on the shaping mould is then positioned onto the hot press machine, as seen in Figure 8. It is a high pressure, low strain rate material processing machine for compact material forming at high temperature. It consists of an upper and lower mould, the former is higher in temperature for the compression of solid substances, while the latter is designated for the cooling and hardening process. A predefined temperature and compression duration can be set to automate the whole process. This avoids compression overheating which affects the solid substance characteristic.

After cooling, completed particle boards are edge-trimmed for cosmetic reasons. They are shown in Figure 9.

- Hardware Measurement

Hardware measurement involves the setup of free space measurement technique, the high temperature dielectric probe, and their corresponding measurement software (Agilent 85071 E and Agilent 85070 E software). Prior to measurements, calibration of the measurement system (PNA network analyzer, free space measurement system, and high temperature dielectric probe kit) must be taken into consideration, besides the theoretical understanding of both measurement setups.

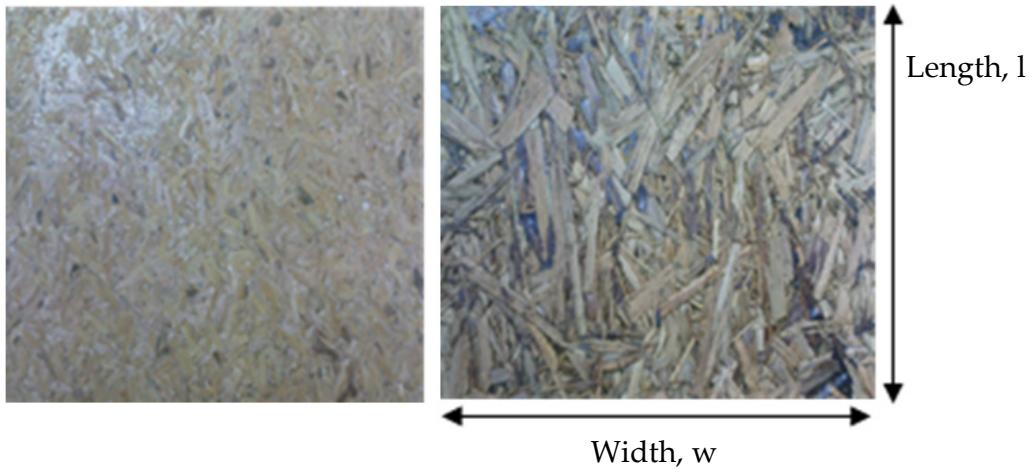**Figure 8.** Hot Press Machine

Figure 9. Paddy waste particle boards

(a)   (b)

Figure 10. (a) coaxial cables (b) Agilent 85052 D calibration kit

Before proceeding with the measurement, calibration of coaxial cables using a known dielectric and length reference board is carried out. The calibration is done at both transmitter and receiver to remove undesired errors and ensure measurement accuracy. Full two-port calibrations using SOLT (Short – Open – Load – Through) standard is performed using the Agilent 85052 D 3.5 mm calibration kit, which contains test adapters and a torque wrench [11-16]. Figure 10 shows the coaxial cables and the calibration kit used for this purpose.

- Free Space Measurement Technique

The procedure described in Figure 11 is used for the paddy wastes particle boards measurements. Its setup, shown in Figure 12, consists of the Performance Network Analyzer (PNA), Agilent 85071 E measurement software, horn antennas, coaxial cables, adaptors, and the particle board as the Material under Test (MUT).
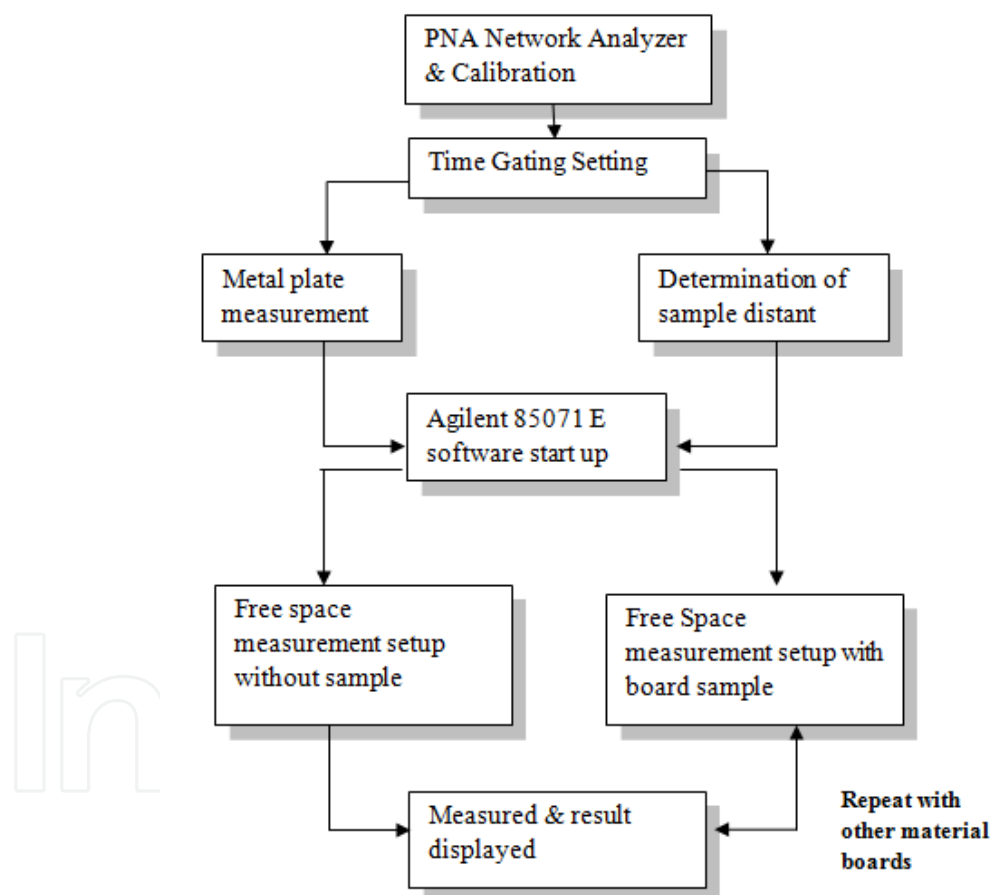

Figure 11. Free Space Measurement technique measurement procedure

For this technique, a MUT calibration setup needs to be performed. A reference board with known dielectric constant is first placed between the two horn antennas. In this case, a copper plate is used as the reference board, with its dielectric constant displayed on the Agilent 85071 E Material Measurement software display. Next, the reference board is removed to ensure the dielectric constant, ε_r is equal or near to 1, similar to air. When both

reference board and air are similar to their actual dielectric constants, the calibration setup process is considered complete.
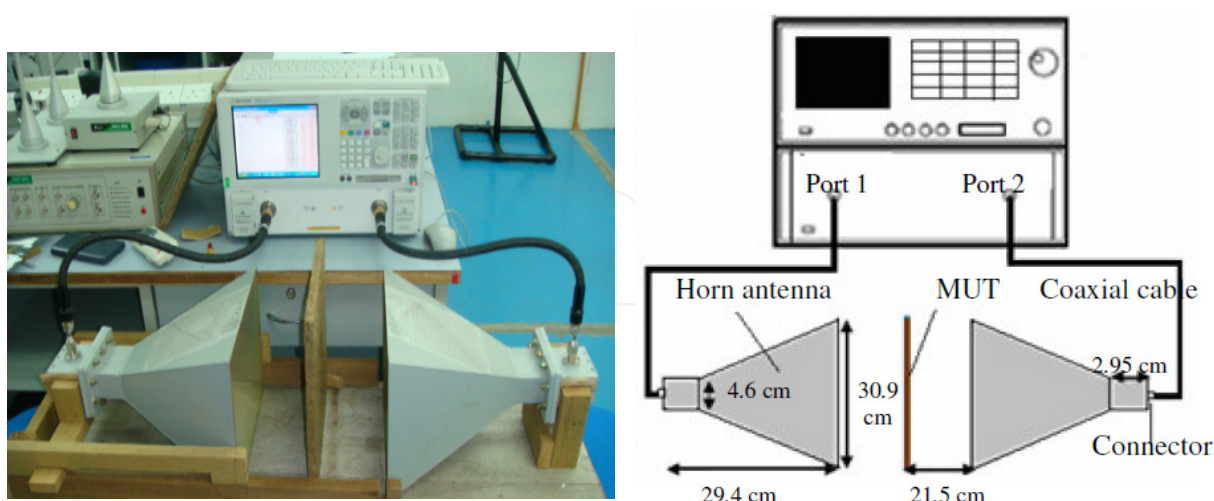

Figure 12. Free Space Measurement Setup

The dimension of the horn antennas used in this setup is 30.9 cm x 23.85 cm x 29.4 cm. The antenna size influences the transmitter-receiver distance, a smaller antenna size results in a shorter distance between the two antennas. The length of the coaxial cable must also be considered, since a longer cable results in a higher attenuation and a weaker signal at the transmitting horn [14-16]. The two antennas are directed into the line of sight (LOS) path and polarized horizontally relative to the MUT to ensure accuracy.

The minimum MUT-antenna distance is another important determining factor to ensure accurate dielectric properties extraction. This distance can be determined by applying the time gating setting at the PNA network analyzer when the sample is placed during calibration, as shown in Figure 13. This feature is useful in lowering the effect of reflections appearing as noise in the time domain response. Average S_{11} measured using a non-metallic and metallic plate must produce at least 40 dB in difference. Three peaks shown in the network analyzer, the first being the response caused by the transmitting horn, the second is for the time domain gating feature while the third is the response caused by the receiving horn. In this example, the difference between the two plates is 52.713 dB, which sufficient to optimize the distance between the two horn antennas. For each MUT measurement, a set of dielectric constant and loss factor, listed in a table, is produced. Besides that, graphical plots can also be viewed using the 85071E measurement software.

- High Temperature Dielectric Probe Measurement method

We have also included the investigation of an Agilent 85070 B High Temperature Dielectric Probe Kit in determining paddy wastes' dielectric properties. The system consists of an Agilent 85070 D High Temperature Dielectric Probe, Agilent Performance Network Analyzer (PNA), and Agilent 85070 B software. This technique is

easy to perform, time-effective and simple, without requiring any special fixtures or containers. MUTs, either rice husk board or rice straw board, is pressed using the dielectric probe as shown in Figure 14. This probe propagates signal into the MUT [17], and the resulting measured reflections are then converted into dielectric properties values via Agilent 85070B software. This system is capable of determining dielectric properties up to 20 GHz.
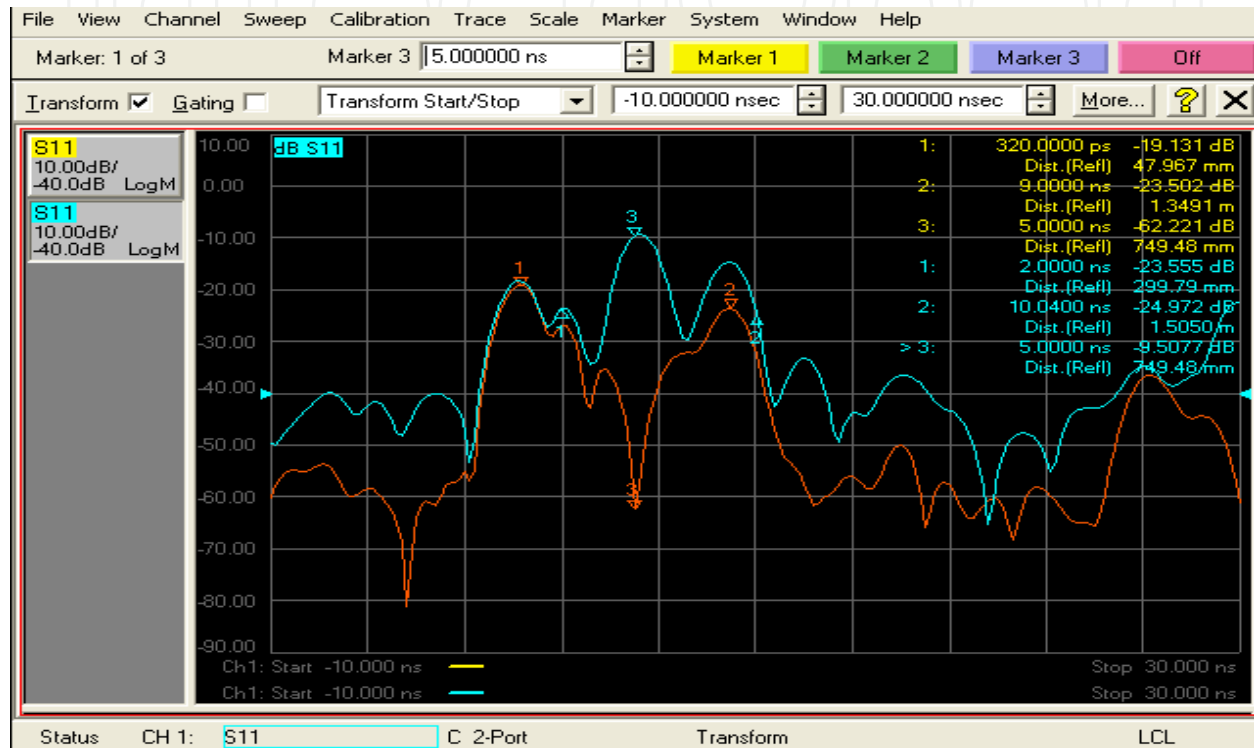

Figure 13. Time domain gating setting

Prior to usage, the High Temperature Dielectric Probe Kit needs to be calibrated using three elements and the software shown in Figure 15(a). The elements are air, a metallic shorting block, and water. This shorting block is shown in Figure 15(b), while for water, users need to ensure that no air bubbles exist. Upon completion of calibration, the MUT can then be placed underneath the probe for measurements.

In this work, the rectangular paddy waste boards and cylindrically-shaped Barium Strontium Titanate (BST) blocks are considered for measurements. Paddy waste boards measurements are conducted at 16 different points, seen in Figure 16 to ensure measurement accuracy. On the other hand, BSTs are measured at five points at its top and bottom, respectively. The middle section of this BST block was not considered due to the high possibility of obtaining inaccurate results. This is mainly due to high possibility of air gap existence between the dielectric probe and the BST material, caused by its curved surface.
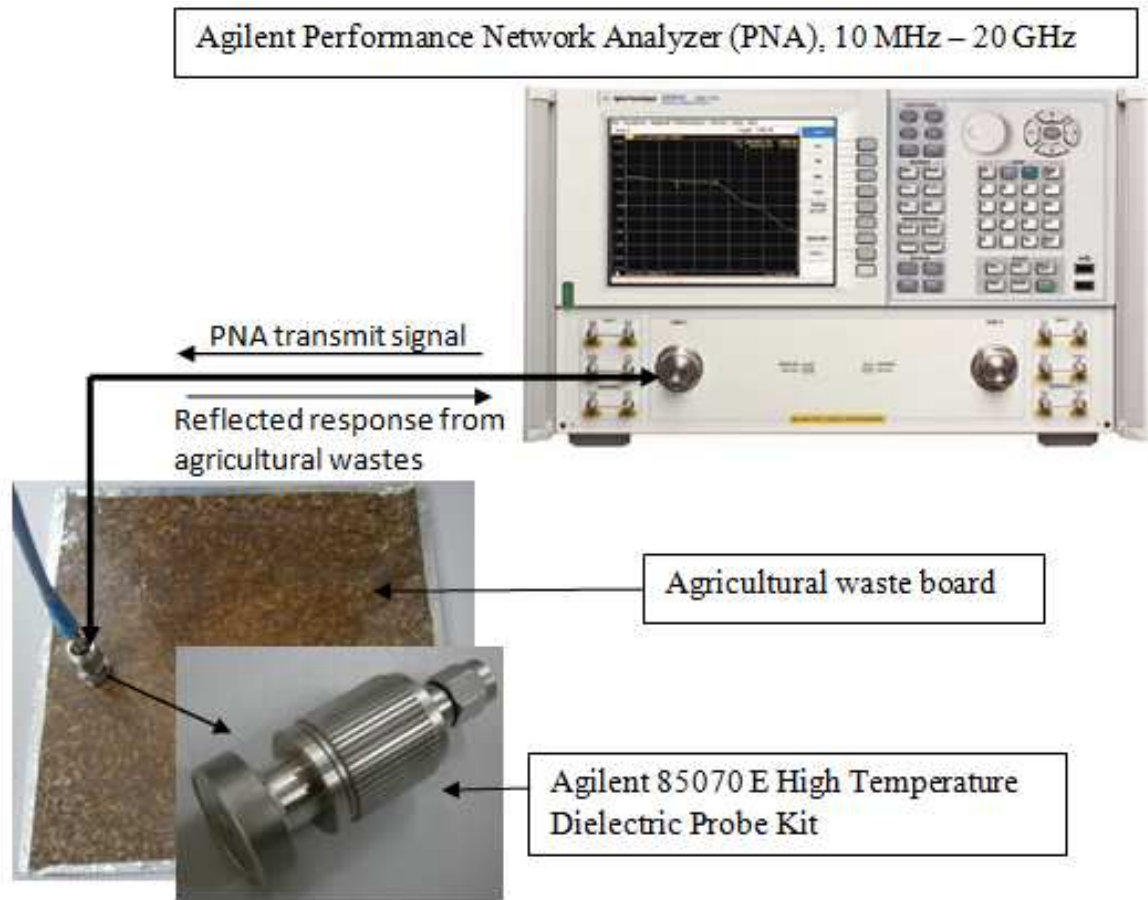
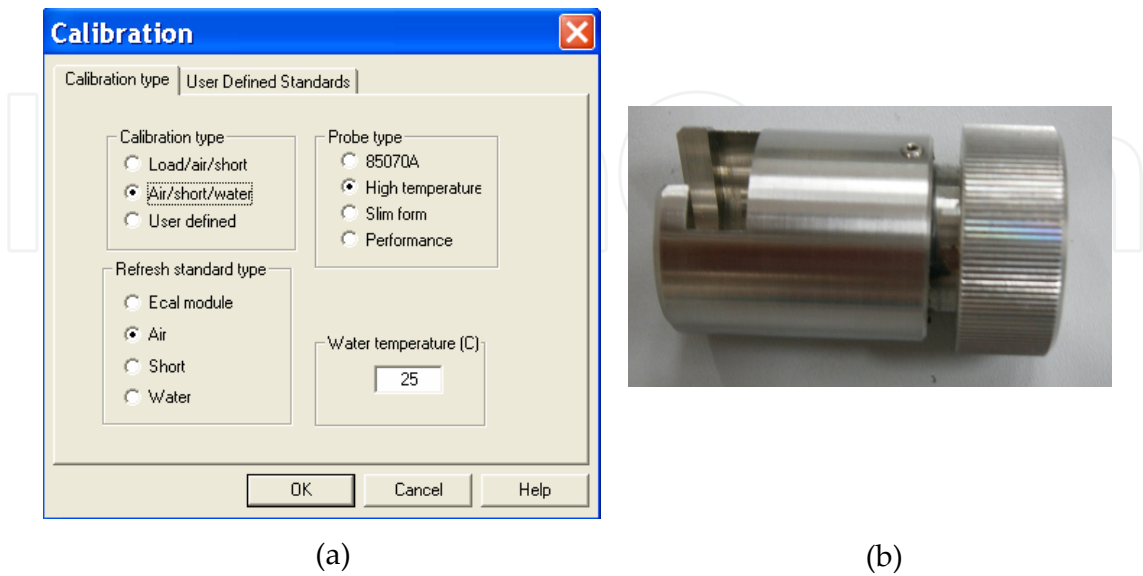**Figure 14.** High Temperature Dielectric Probe System

(a)   (b)

Figure 15. Calibration components (a) software window for calibration type selection (b) shorting block
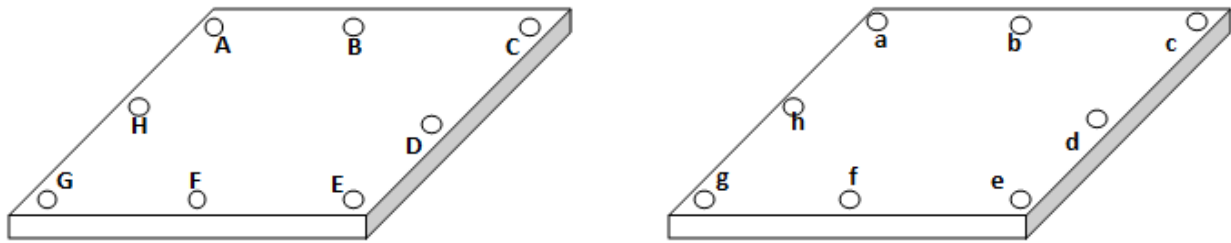
Figure 16. Measurement of 16 different location points on the MUT (a) top view (b) bottom view.

- Results:

Free Space Measurement Technique and High Temperature Dielectric Probe Kit had been utilized to obtain the dielectric properties in different settings, as follows:

1. Dielectric properties of rice husk either PF or UF resins.
2. Dielectric properties for two paddy waste materials (rice husk and rice straw), with different PF resin percentage (10 %, 30 % and 50 %)
3. The accuracy of dielectric properties using different horn-to-MUT distances, investigated using both types of boards.
4. Changes in dielectric properties of rice husk boards with frequency.
5. Comparison Free Space Measurement Technique and High Temperature Dielectric Probe using 50% PF of rice husk and rice straw MUTs.
- Dielectric properties of rice husk using both PF and UF resins

From the Table 2, it can be observed that the dielectric constant, ε' of the rice husk MUT using PF resin is higher than for UF. For 10% PF and UF content, the dielectric constant of MUT with PF adhesive (3.2355) is larger compared to MUT with UF adhesive (2.8907). This similar observation is also consistently found for 30% and 50% composition for both resins. Besides UF being a low water absorbent, the predominantly higher dielectric constant found in PF-MUTs is due to its higher liquid density, causing a higher moisture level compared to the rice husk boards with UF composite [16].

Resin	Percentage, %	Dielectric Properties	
		ε'	ε''
PF	10	3.2355	0.2742
	30	3.2745	0.2680
	50	3.5813	0.4393
UF	10	2.8907	0.2215
	30	3.4054	0.3286
	50	3.6808	0.2725

Table 2. Dielectric properties of rice husk boards fabricated using different resin percentage.

The loss tangent of the rice husk particle boards are quite similar for both resin PF and UF seen for all 10%, 30%, and 50% UF and PF composition. This is due to densification of rice husk rectangular board. When the electromagnetic radiation is incident on the material

board's surface, the amount of reflection experienced by the board is higher than transmission into the material [16]. Hence, this may described as an energy loss process, as more signal is reflected compared to absorbed.

- Dielectric properties for two paddy waste material types (rice husk and rice straw), with different PF resin percentage.

Material	Percentage, %	Dielectric Properties	
		ε'	ε''
Rice Husk	10	3.2355	0.2742
	30	3.2745	0.2680
	50	3.5813	0.4393
Rice Straw	10	1.9061	0.135
	30	2.0127	0.123
	50	2.7358	0.2236

Table 3. Dielectric properties of the two material boards fabricated using different percentage of Phenol Formaldehyde (PF) resin.

Paddy waste is a known non-magnetic material [14]. Measured ε' and ε'' of boards fabricated using a varying UF and PF resins' concentrations (10 %, 30 % and 50 %) are given in Table 3. ε_r increases as the concentration of UF and PF are increased from 10% to 50%. This is due to higher volume fraction of the chemical resin in the composite. ε'' values are expected to be greater than or equal to zero, while the negative ε'' values are caused by measurement uncertainties. Thus, obtained dielectric loss tangents being larger than zero indicate measurement accuracy. To summarize, between the frequency range of 2.2 GHz and 3.3 Ghz, the loss tangent and dielectric constant showed an increasing trend with the rising moisture content provided by PF and UF resins.

- Accuracy of dielectric properties using different horn-to-MUT distances investigated using two types of agricultural waste material boards.

This investigation scope is aimed at identifying the relationship between measured dielectric properties using three different MUT-to-horn distances. Table 4 shows the dielectric constant, ε', and tangent loss, ε'', variation between 2.2 GHz and 3.3 GHz at room temperature of 27°C. The results shows that the dielectric constant, ε', steadily decreases as the distance is increased from 215 mm to 475.5 mm.

This decreasing trend can also be consistently observed for both rice straw and rice husk MUTs, as well as across the different PF resin contents. This is due to the decreased penetration depth into the material boards caused by an increased MUT-to-horn distance, and vice versa for shorter distances. In other words, the longer MUT-to-horn distance caused attenuation and scattering of the emitted signals, leading to less absorption by the MUT [6]. Due to this, ε' is lower when measured using a longer distance, as test signals are unable to reach the MUTs. On the other hand, an opposite trend is seen for ε'' when increasing this measurement distance. In general, it can be said that the paddy waste boards

are unable to be measured accurately due to the weak signal when measurement distance is lengthened.

Materials	Percentage, %	Distance (mm)					
		215		377		475.5	
		ε'	ε''	ε'	ε''	ε'	ε''
Rice Husk	10	3.2355	0.2742	3.1386	0.4766	2.8854	0.4964
	30	3.2745	0.2680	3.4727	0.617	3.249	0.6513
	50	3.5813	0.4393	4.4912	0.484	4.0305	0.5389
Rice Straw	10	1.9061	0.135	1.8905	0.2153	1.8138	0.246
	30	2.0127	0.123	1.974	0.2106	1.9068	0.2335
	50	2.7358	0.2236	2.639	0.3722	2.4848	0.3921

Table 4. Dielectric properties of rice husk and rice straw with a varying MUT-to-horn distances.

- Changes in dielectric properties of rice husk material boards with frequency.

Table 5 presents the variation of measured dielectric properties according to frequency. This shows that the frequency significantly affects MUT's loss tangent (ε''), which rises with the increasing frequency. In most cases, this frequency-loss tangent relationship is nearly linear. On the other hand, the ε'' result obtained in the Table 5 are higher at both ends of the test frequency range, and is slightly decreasing in the middle. This tendency is observed for all three different percentages of PF resins for the rice husk particle boards. This discrepancy is caused by the propagation of indirect signal known in this measurement technique, thus degrading the accuracy of the measurement results [18-19].

Freq (GHz)	Percentage of Phenol Formaldehyde								
	10%			30%			50%		
	ε'	ε''	ε' (%)	ε'	ε''	ε' (%)	ε'	ε''	ε' (%)
2.2	3.4897	0.3284	100	3.9276	0.4859	100	5.0302	0.2363	100
2.3	3.4742	0.2888	99.56	3.9074	0.4571	99.49	4.9839	0.1929	99.08
2.4	3.4046	0.2632	97.56	3.8234	0.4165	97.34	4.8626	0.1563	96.65
2.5	3.3571	0.2675	96.16	3.7452	0.4266	95.29	4.7671	0.1809	94.69
2.6	3.311	0.2615	94.79	3.673	0.4222	93.36	4.6695	0.1813	92.64
2.7	3.2514	0.2637	92.99	3.604	0.4253	91.48	4.5813	0.196	90.75
2.8	3.1997	0.263	91.40	3.5342	0.4261	89.54	4.4919	0.2052	88.80
2.9	3.1543	0.2681	89.98	3.4711	0.4341	87.75	4.4135	0.2241	87.05
3.0	3.1154	0.2716	88.75	3.4175	0.4406	86.20	4.3473	0.2358	85.55
3.1	3.0753	0.2737	87.46	3.3596	0.4426	84.50	4.27	0.2509	83.77
3.2	3.299	0.2852	92.46	3.2932	0.4591	82.52	4.1956	0.2813	82.03
3.3	2.9902	0.2999	83.1	3.2353	0.4764	80.76	4.1196	0.3127	80.22

Table 5. Measured rice husk material board's dielectric properties across frequency

Although values of the dielectric properties decreased with the increasing frequency, the linear slope performed differently, depending on the agricultural waste type and moisture content. Besides this trend, its decrease with UF and PF percentage is also evident in Table 5 and Figure 17. However, there exist a set of stray measurement value with 10 % PF content at 3.2 GHz. This error is due to uncertainty of the sample form and size as well as the surface roughness of the material boards [20], which degraded its accuracy. It must be noted that the calculation is only valid for the geometrically ideal sample, which could be avoided by applying a very strict sample preparation process. In short, frequency, loss tangent and dielectric constant will affect the amount of energy that is dissipated in agricultural waste materials. Higher loss tangent results in higher microwave signal absorption by the boards, and conversely, a lower dielectric constant favors higher heat absorption in the fibers [19-21].
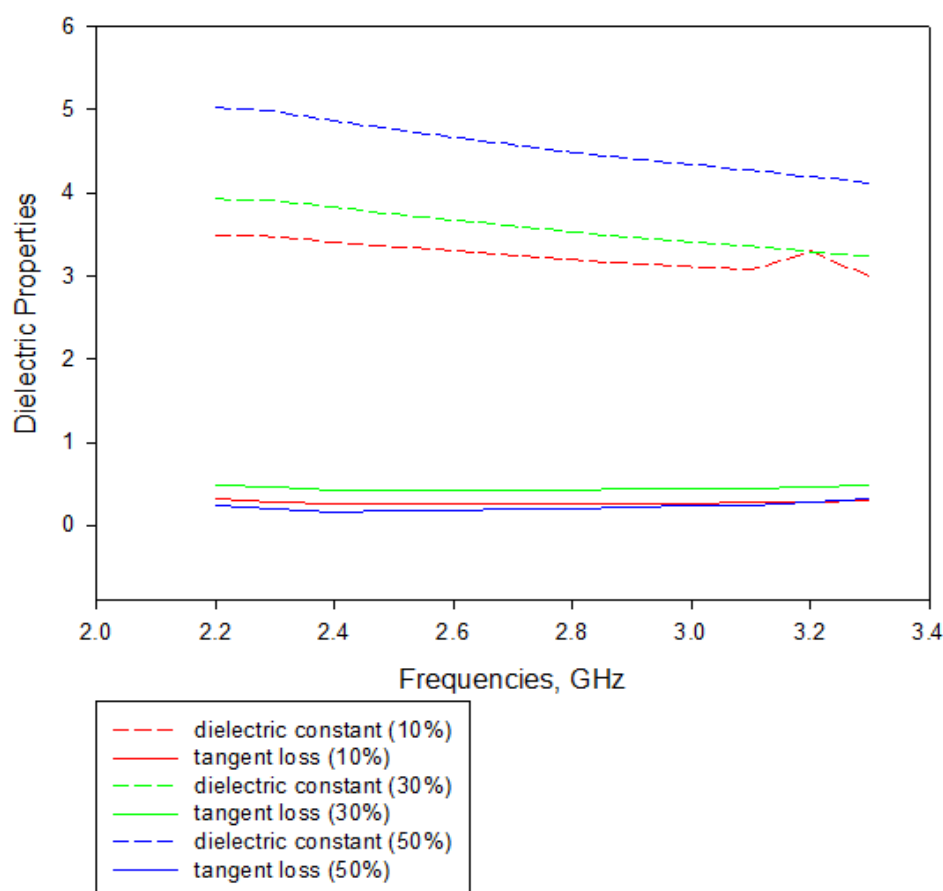

Figure 17. Dielectric constant and tangent loss across frequency

- Comparison Free Space Measurement Technique and High Temperature Dielectric Probe using 50% PF of rice and rice straw MUTs

A comparison of measured rice husk's dielectric properties using Free Space Measurement Technique and High Temperature Dielectric Probe Kit is shown in Figure 18. Tangent loss evaluation of a similar rice husk board (with 50% resin) using these two different techniques is producing an excellent agreement. This is also seen for rice straw board measurement, yielding an almost similar reading. Meanwhile, measurement of dielectric constant using

the two measurement techniques shows that the High Temperature Dielectric Probe Kit produced higher dielectric constant values. This is caused by the High Temperature Dielectric Probe's ability to feed test signals directly into the MUT. The MUT-to-horn distance which exists in the Free Space Measurement Technique introduces an additional uncertainty factor, potentially causing loss between signal paths. Besides that, the measurement are also affected by other uncertainties - inconsistent MUTs' geometry, roughness and surface homogeneity. Additional limitations may arise from the systemic uncertainty of the particular instrument, and the imperfections of the test fixture and setup.
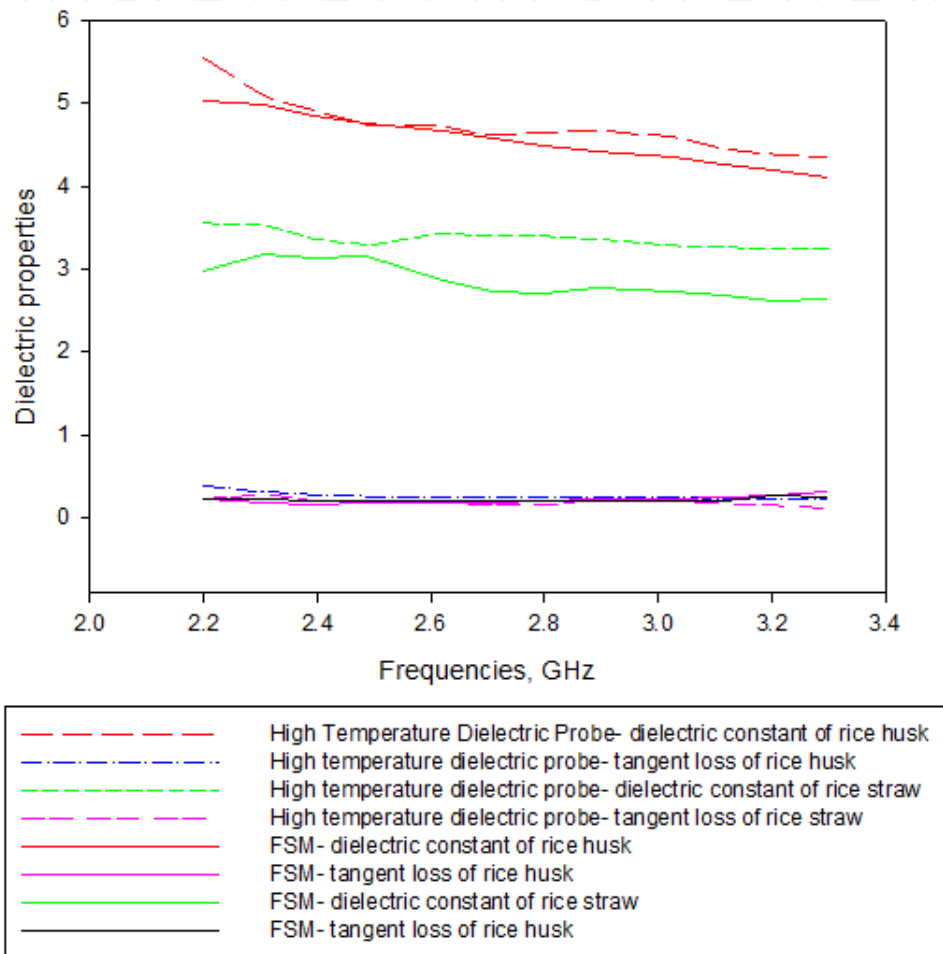

Figure 18. Dielectric property measurements of rice husk and rice straw using two different measurement techniques.

- Status:

In summary, we have described two effective methods to determine the dielectric properties of custom-made paddy waste particle boards Its procedure, advantages, limitations and operation in several different configurations are also carefully investigated and explained. This has laid the foundation for a better understanding of dielectric behavior, which will assist microwave or electronic components' engineers in optimally designing their components, and promoting the use of an alternative, sustainable material.

3. Further research

Other boards fabricated using different agricultural waste materials should also be investigated. This will also depend on the waste material's availability, based on the geographical region and type of agricultural/economic activities. On the other hand, the current scope can be expanded to evaluate boards with different thicknesses, as MUT's thickness could affect measurement accuracy. It is also evident that improvement on the measurement setup is relevant, especially on the free space measurement technique.

4. Conclusion

A systematic procedure to fabricate and evaluate custom particle boards made from two types of agricultural waste product is explained in detail. In total, six variation of waste boards are evaluated, and they are fabricated using different paddy waste types and different bonding resins, i.e. Urea Formaldehyde (UF) and Phenol Formaldehyde (PF). Two standard setup and procedures for measuring their dielectric properties between 2.2 GHz and 3.3 GHz are presented and compared. The results, calibration and factors influencing measurement accuracy are then discussed. Rice husk-based MUTs are measured to be higher in terms of dielectric properties compared to rice straw-based MUTs. This is mainly due to the former's small particle size, enabling a larger surface area which absorbs more test signal. Comparison of two measurement methods presented shows a good agreement, with uncertainties of less than 15 %. The measurements have also proven that MUTs fabricated using PF is higher than UF due to the ability of the former to absorb moisture. The measurement results presented will be potentially useful in encouraging the use of such sustainable, renewable materials at microwave frequencies.

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