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Research Article

Comparison of the Microwave Absorption Properties of *Opuntia ficus-indica*, *Agave atrovirens*, and *Cocos nucifera* L. Husk

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In this work, a comparison of the microwave absorption properties of *Opuntia ficus-indica* cladodes, *Agave atrovirens* branches, and *Cocos nucifera* L. husk samples was performed. The study was carried out by inserting dry and powdered samples of these organic materials transversely and in the middle of a rectangular waveguide, for which scattering parameters S_{21} and S_{11} were measured to estimate the absorption coefficient. These measurements were compared to determine the material that behaves the best as a microwave absorber with a view to develop future low-cost and eco-friendly products by reusing agricultural waste. Specifically, *Agave atrovirens* sample showed the best performance, having an average value of absorption coefficient of 0.4218, while its maximum was 0.5792 at 9.706 GHz within the range from 8.005 to 13 GHz.

1. Introduction

Enhancement of environmental quality is an internationally accepted goal. Historically, the major efforts to maintain and enhance environmental quality have focused on problems caused by urban centers. This emphasis has been due to pressing problems in controlling industrial pollution, treating domestic liquid wastes, disposing of municipal solid wastes, and perhaps an instinctive feeling that agriculturally related environmental quality problems were uncontrollable and/or minor. It is worth-mentioning that only recently attention has been given to the waste problems of agriculture and, within these recent years, it has been documented that agriculturally related pollution is not minor and deserves more attention of scientists, engineers, and administrators interested in the enhancement of the environment [1]. Mexico is not exempt from this situation, where large amounts of waste are not exploited correctly. Just to mention some examples, it can be referred to *Opuntia ficus-indica* (OFI) [2] or cactus pear, *Agave atrovirens* (AA) or maguey [3], and *Coco nucifera* L. husk (CN) [4] as some common agricultural products which eventually generate waste in this country.

In the case of OFI, by August 2017 in the zone of Milpa Alta belonging to Mexico City, it was reported that 10 tons of the 20,000 produced annually ended as waste [5, 6]. Regarding AA, this kind of agave belongs to a group of more than 200 endemic varieties of Mexico of which over 17,000 tons bagasse are generated every year in the country and, given that the carbon content of this product is 45%, it is estimated that this waste would generate more than 28,000 tons of carbon dioxide per year [7]. Finally, for CN, it is worth-mentioning that Mexico is a leader in Latin America producing this agricultural product, having in the state of Guerrero the greatest production of little more than 4,000,000 tons and from which large amounts of waste (husk) can be used in the manufacture of products [8].

In this work, dry samples of OFI cladodes, AA branches, and CN husk are the target due to their relative abundance in the country, and like all organic matter they have a high carbon content, an element that favors the absorption of electromagnetic waves in the microwave region [9, 10]. These three materials come under the category of agricultural wastes and have a great potential of being used as good microwave absorbers, which are essential elements of anechoic chambers, enclosures that are used for electromagnetic compatibility (EMC), or antenna measurements. These anechoic chambers have their interior walls cover by pyramid-shaped absorber materials (mainly polyurethane) that are intended to prevent the reflection of waves to devices under test, avoiding interference during measurements, while the outside of the walls blocks the entry of unwanted electromagnetic waves [11]. In addition to the above-mentioned, absorbers are used for electromagnetic interference (EMI) reduction inside wireless electronics assemblies, since electronics operating at high microwave frequencies can have problems with the emission of high-frequency noise which will hinder the performance of the device. Finally, it is important to highlight that the absorbers are also utilized for antenna patterns shaping and radar cross-section [12].

The three proposed organic materials are an alternative to commercial polyurethane absorbers, since it was found that agricultural wastes like banana leaves, sugarcane bagasse, and rice husk can be used for the same purpose [13]. These organic absorbers are composed of renewable materials and eliminate the toxic gas release problem observed in commercial materials such as polyurethane under high power test conditions. They are cost-effective materials and can be used to make eco-friendly microwave absorbers with acceptable results [14–17]. In this work, a comparison of the absorption properties at microwave frequencies for three different organic materials was performed in order to find out the one that offers the best performance.

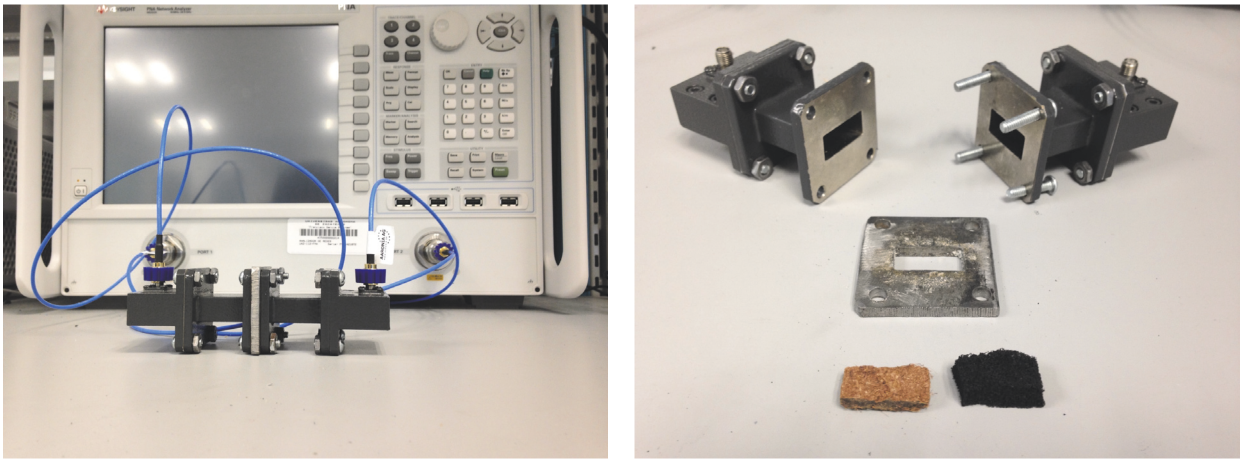
2. Materials and Methods

2.1. Experimental Setup: Measurements. For achieving a comparison of the absorption coefficient A in the microwave region of three organic materials (OFI, AA, and CN), two-port measurements using a rectangular waveguide were performed. The experimental setup consisted of a WR90 straight rectangular waveguide with a sample holder placed in the middle of it. The dimensions of the samples were set to match those of the waveguide cross-section (2.286 cm high and 1.016 cm wide), while the thickness was 6 mm. The total waveguide length including the sample holder was 114 mm existing 54 mm between the input port and the sample and the same between the sample and the output. It is worth-mentioning that both ports of the waveguide were connected to the ports of an N5222A Keysight ® Vector Network Analyser (VNA) [18] using SMA connectors and 50 Ω low-loss coaxial transmission lines. The VNA was calibrated using an 85521A Keysigth 3.5 mm Cal Kit [19] from 6.565 to 13 GHz to measure S_{21} and S_{11}, which lead to computing the absorption coefficient $A=1-|S_{11}|^2-|S_{21}|^2$ at frequencies above the cutoff frequency of the TE_{10} mode. The organic samples were made of powdered and dry organic materials (OFI, AA, and CN) which were compacted in the sample holder. The powdered materials were moistened to make a coir paste filling the sample holder while it was on a flat surface; pressure and heat were applied to dehydrate at 180°C and then a brick whose dimensions were the same as those of the sample holder was created. The air gaps were less than 1 mm wide and much smaller than the smallest wavelength used corresponding to the highest frequency of 13 GHz. Finally, in order to compare with commercial materials used for pyramidal absorbers inside anechoic chambers, a polyurethane sample with dimensions very similar to those of organic samples was considered. This kind of absorber from ETS-Lindgren ® was the EMC-24PCL, an Ultra-Broadband Microwave Absorber [20]. Figure 1 shows (a) the assembled experimental setup and (b) the components: the waveguide, the sample holder, and organic materials.

2.2. Numerical Simulations. In order to show the waveguide performance in terms of propagation with a sample of absorber material inserted, i.e., polyurethane, a simulation using advanced electromagnetic simulation software based on the finite element method was carried out, where the same dimensions described in Section 2.1 for the experimental setup were considered. Firstly, the waveguide was simulated at 18 GHz in order to observe the cutoff frequencies for the 4 TE modes (TE_{10}, TE_{20}, TE_{01}, and TE_{11}). The simulation considered wave ports at the entrance and the exit of the waveguide for which integration lines were defined. The input power for the 4 modes was 1W. Geometrically and for boundary condition purposes, 3 regions that constitute the waveguide were considered: air before and beyond the sample, polyurethane for the sample, and copper for the wall of the waveguide. Likewise, on the outside of the waveguide, a radiation boundary box was defined. Material for the sample was defined considering frequency-dependent dielectric properties reported in [21]. The parameter obtained by simulation was the electric field for the 4 TE modes. Later, a simulation only considering the TE_{10} mode at the frequency where polyurethane showed the highest absorption coefficient for measurements was performed. Figure 2 shows the geometry used for the simulation.

3. Results and Discussion

In the same order in which methodologies used in this work were described in the previous section, results obtained



(a) (b)

Figure 1: (a) The assembled experimental setup and (b) its components.

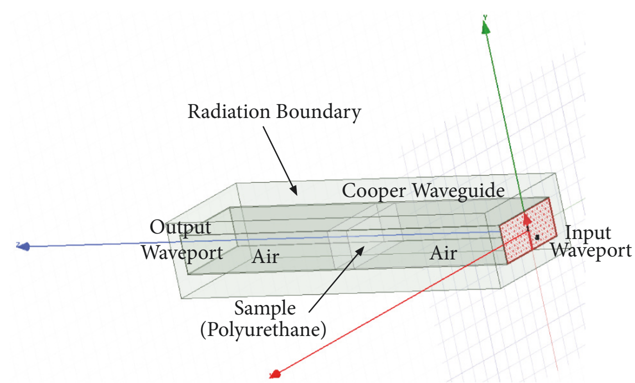


Figure 2: Geometric model for the simulation of the rectangular waveguide with an absorber material sample.

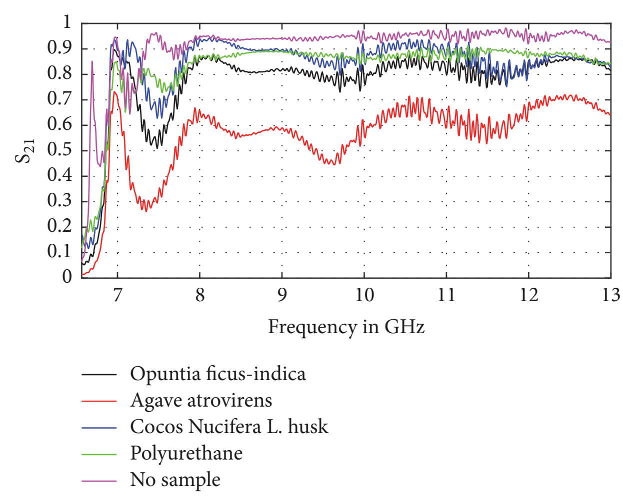


Figure 3: S_{21} for the waveguide considering samples of organic materials, polyurethane, and no sample.

for measurements and numerical simulations and for the waveguide are presented, respectively. The experimental setup was intended to compare the absorption properties at microwave frequencies of the three organic materials along with polyurethane and the empty device (no sample, free space), while numerical simulations were performed to show the waveguide behavior in terms of propagation when inserting a sample of dielectric material such as polyurethane.

3.1. Experimental Setup: Measurements. Regarding measurements based on the rectangular waveguide with samples inside, S_{21} and S_{11} were measured considering it as a two-port network. In this case, a comparison in the frequency domain of the absorption coefficient A by the measurement of s-parameters was performed. The comparison was done in order to find out the material that best works as microwave absorber from 6.565 to 13 GHz and above the cutoff frequency of the TE_{10} mode (6,5572 GHz). Figures 3, 4, and 5 show comparisons for S_{21}, S_{11}, and absorption A for the 3 organic materials along with polyurethane and free space (empty waveguide).

It is clear that at frequencies above 8.005 GHz, more stability is observed because the cutoff frequency for TE_{10} mode has been considerably exceeded. In Figure 5 it is demonstrated that AA shows notoriously the highest absorption coefficient A_{max} among the three organic materials with a maximum value of 0.5792 at 9.706 GHz and average absorption coefficient $\overline{A}$ of 0.4218. The other two organic materials (OFI and CN) show lower absorption coefficients at 9,706 GHz of 0.3027 and 0.1991, respectively, while polyurethane also shows a lower absorption coefficient of 0.2365 when compared with AA at the same frequency of 9.706 GHz. It is important to emphasize that OFI, CN, and polyurethane show average absorption coefficients of 0.2295, 0.1632, and 0.1965, respectively. Table 1 includes this information from 8.005 GHz to 13 GHz for comparison purposes.

Table 1: Comparison of average absorption coefficient A for the 3 organic materials and polyurethane from 8,005 to 13 GHz.

Material	$\overline{A}$	A_{max} @frequency	A @ 9.706 GHz
AA	0.4218	0.5792 @ 9.706 GHz	0.5792
OFI	0.2295	0.3514 @ 9.949 GHz	0.3027
Polyurethane	0.1965	0.2454 @ 11.29 GHz	0.2365
CN husk	0.1632	0.3461 @ 11.73 GHz	0.1991

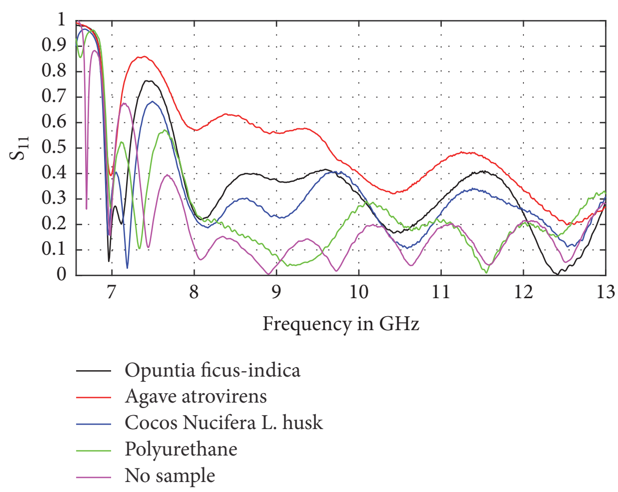


Figure 4: S_{11} for the waveguide considering samples of organic materials, polyurethane, and no sample.

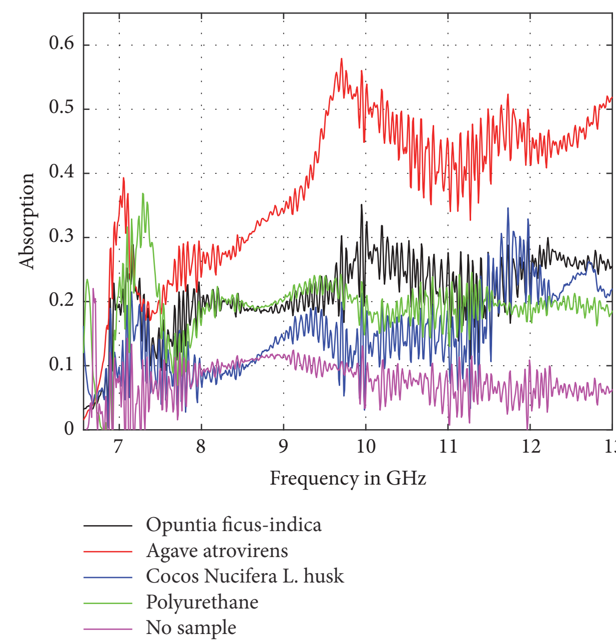


Figure 5: Absorption A for the waveguide considering samples of organic materials, polyurethane, and no sample.

3.2. Numerical Simulations. As mentioned in Section 2.1, numerical results regarding the electric field configurations were obtained for 4 TE modes. The magnitude of the electric field was plotted for the rectangular waveguide at 18 GHz with a polyurethane sample inserted in it. This frequency was chosen because it exceeds the cutoff frequency of the TE_{11} mode. It is important to highlight that an input of 1W for TE modes was set and a color scale from 9.2137 mV/m to 5.5580 KV/m was considered. The lower face of the rectangular prism (z=0) represents the input port with the waveguide extended along the z-axis, while the upper is the output port. Figure 6 shows the configurations for the magnitude of the electric field in the hollow parts of the waveguide and through the polyurethane sample and the geometry where the distribution is altered due to the presence of the sample with different dielectric properties.

Considering only TE_{10} mode at 11.29 GHz, the frequency where measured polyurethane showed the highest absorption coefficient from 8.005 GHz to 13 GHz, a simulation with the same characteristics described in Figure 2 was performed in order to highlight the absorption phenomenon. In Figure 7 an instant configuration (phase=90°) for the magnitude of the electric field at the referred frequency is shown where the prism in the central part represents the sample volume.

The electric field shows the typical behavior in a rectangular waveguide described in [22], where it can be seen that for the TE_{10} mode E_x and E_z are zero and that E_y depends on H_x, where H_x solution of the partial differential equation $\partial^2 H_x/\partial z^2 + (\mathcal{E}\kappa^2 - \beta^2) H_x$ is proposed from Maxwell's equations. The expressions for E_y in the three sections involved (air: I, sample: II, and air: III) are described in [22] as follows:

$$E_y = j\omega\mu_0 \frac{\partial H_x}{\partial z} \begin{cases} \dfrac{1}{\kappa^2 - \beta^2} & : \mathrm{I} \\ \dfrac{1}{\varepsilon\kappa^2 - \beta^2} & : \mathrm{II} \\ \dfrac{1}{\kappa^2 - \beta^2} & : \mathrm{III} \end{cases} \quad (1)$$

with H_x defined as

$$H_x = H_0 g(z) e^{j(\omega t - \beta x)} \quad (2)$$

where g(z) is an antisymmetric function about the center of the waveguide.

The variation in the magnitude for the electric field through the sample with complex permittivity $\epsilon = \varepsilon\epsilon_0 = \epsilon_0(\varepsilon' - j\varepsilon'')$ can be verified in the expression corresponding to Section 2 in (1).

4. Conclusions

In this article the subject of the absorption of electromagnetic waves was approached focusing on microwaves,

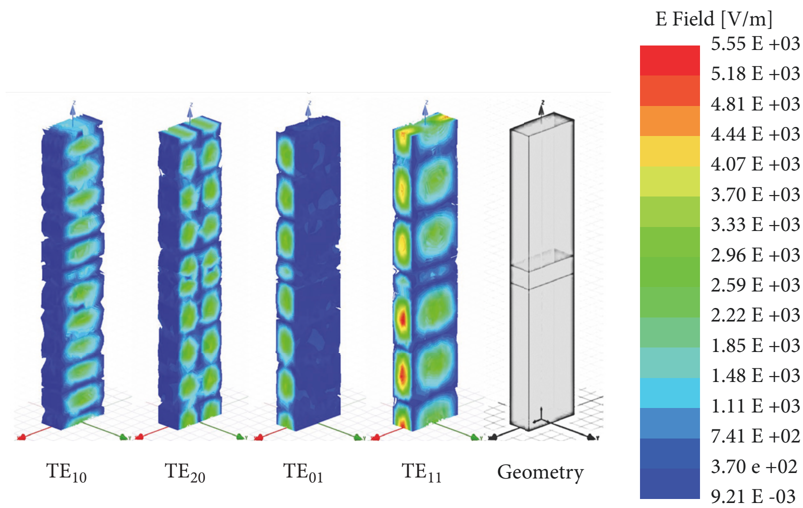


FIGURE 6: Simulated configurations for the magnitude of the electric field for 4 TE modes at 18 GHz with a polyurethane sample inserted inside the rectangular waveguide.

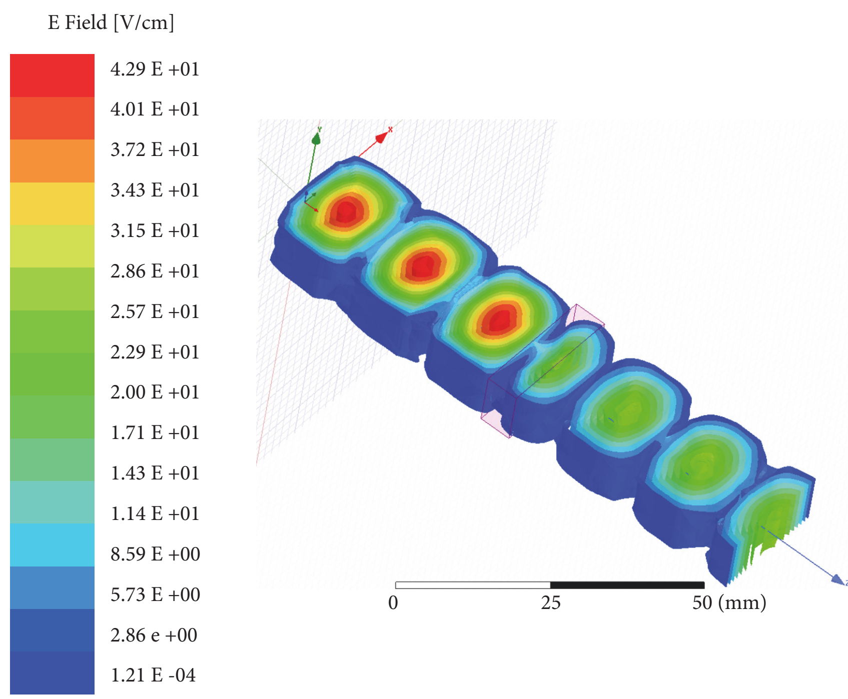


FIGURE 7: Instant configuration at 11.29 GHz and phase=90° for the magnitude of the electric field for TE_{10} mode.

since, in the field of telecommunications and depending on the application, it is sometimes necessary that waves are concentrated in one place or device, while in other cases the opposite is needed. For this reason, materials with relatively good absorption properties at certain frequencies are useful when it is wanted to absorb in order to avoid affecting the operation of another neighboring device. In a commercial way, polyurethane is used in the manufacture of absorbers that are placed in anechoic chambers; that is why in this research a comparison of absorption properties is carried out with samples of 3 different organic materials, such as OFI cladodes, AA branches, and CN husk, which were compared with the case without sample (free space). In this comparison, parameters S_{21}, S_{11} and absorption coefficient A for a rectangular waveguide with samples inside were obtained. It was observed that AA showed the highest absorption coefficient of the three organic materials along with polyurethane from 8.005 to 13 GHz which was 0.5792 at 9.706 GHz, while the average value in the same range of frequencies for OFI and CN husk was 0.2295 and 0.1632.

In this work, it is concluded that organic waste materials from agriculture such as AA are good candidates for the manufacture of low-cost and eco-friendly microwave absorbers, contributing to the reuse of waste. Future work visualizes the manufacture of commercial pyramidal absorbers based on this organic material through the use of molds and a binder that does not significantly alter its properties to prevent them from crumbling and can be handled. Likewise, its mixture is visualized with materials with carbon forms that help to increase microwave absorption efficiencies, such as carbon nanotubes or related materials.

Data Availability

The signal level measurement data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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