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Measurements of Electromagnetic Radiation Propagation through Biomaterial Samples Based on Harvest Residues

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Abstract: The aim of this research was to determine the efficiency of electromagnetic (EM) radiation absorbers based on biomaterials from harvest residues (soybean straw, wheat straw, and clover straw) for the additional protection and/or construction of residential buildings. To determine their protective properties, the transmission parameter S_{21} was measured through harvest residues in the frequency range from 300 MHz to 5 GHz. Important parameters of the tested samples included sample type, sample thickness, and humidity. The measurement results showed that the transmission parameters decreased with an increase in the sample thickness, moisture, and frequency. Regarding this type of substrate, soybean straw showed the lowest values of parameter S_{21} for all measurements except for the case of the highest amount of moisture (34.48%), for which clover straw showed the lowest value of the transmission parameter. The greatest reduction in the S_{21} transmission parameter was 43.80 dB for a soybean sample of 300 mm thickness at a frequency of 4.93 GHz. These tests were performed on samples that were not additionally structured (additives, pressing, additional shredding, etc.), so it was possible to optimize their structure and conduct further research.

Keywords: biomaterial; electromagnetic radiation; electromagnetic wave transmission; shielding efficiency

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1. Introduction

All life on Earth has been exposed to electromagnetic (EM) radiation since its inception. The history of non-natural sources of EM radiation and fields is rather short and covers only the last century. Non-natural sources of ionizing radiation, such as technical devices, which contain various radioactive isotopes, are considered to be the biggest concern in public health protection today [1]. The increasing number of such sources has led to the normalization and control of radiation levels. For these reasons, there has been a significant increase in the scientific research endeavor to comprehend the influence of EM fields and EM radiation on living organisms [2]. The most efficient approach to protection from EM radiation is the utilization of shielding materials that mitigate the propagation of waves [3]. The increased number of sources of EM radiation conditions the need to secure the space in which we stay and live so that the level of this radiation in that space is significantly reduced. In addition to this increase in the number of sources, the increase in data transfer speed requirements also increases the carrier frequencies of each new communication system (especially the mobile communication system, e.g., 2G: 900 MHz; 3G: 2100 MHz; 4G: 2600 MHz; 5G: 3400–60,000 MHz; 6G: >95,000 MHz. . .; 7G: <3 THz). As the carrier frequency increases, the attenuation of these higher frequencies increases (when propagating in free space), and at the same time, the power of these signals must be increased in order for communication to take place. Therefore, there is a demand and need to reduce the level of this radiation in spaces where people stay, at least in those parts where they spend a large part of their time (bedrooms, children's rooms, and living rooms). At the same time, the most sensitive categories of society should be protected, so special attention should be paid to kindergartens, school classrooms, student and old people's homes, and hospital areas. One of the most effective methods of reducing this level is EM shielding which is applied to several devices of vital importance for their work or the safety of people (medical instruments, aircraft control, and communication systems, electronic devices in satellites, radars, etc.). However, this procedure can also protect living spaces from EM radiation. Therefore, different methods of increased attenuation in the EM field are applied in building materials by forming composites that additionally attenuate EM radiation [4,5]. Idris et al., in their research, [4] examined the effectiveness of a coconut shell-based material that absorbs microwaves. In this research, measurements and simulation calculations were carried out. The best result of the S11 parameter (the lowest value) was shown by the absorber of the square-based shape of −47 dB (measurements) and −46 dB (simulation) at a frequency of 10 GHz. Research by Gupta et al. [5] brings the design of pyramidal and cubic absorbers made of dried banana leaves and dried banana leaves + charcoal. Measurements show that dried banana leaves and dried banana leaves + charcoal show the best reflection result loss of up to −45 dB and −76 dB at 2–20 for the pyramidal absorber and 25 dB and −38 dB for the cubic absorber. These composites mainly use materials that increase the electrical conductivity of building materials (ferrite threads or particles, iron plates or steel reinforcement, nanotubes, and others) but can be harmful to the environment. However, as society strives to achieve a sustainable future, it is imperative to develop innovative strategies that not only protect living species from EM radiation but also align with environmentally sustainable goals [6]. According to the findings of More et al. [6], polymeric materials can be used for protection against EM radiation. The focus of their research is the role of additives and fillers, as well as their effectiveness with regard to the absorption of EM wave energy. In this manner, when developing environmentally friendly technologies for EM shielding, researchers should focus on ensuring that the production processes are sustainable, the used materials are biodegradable and recyclable, and they do not contain harmful chemicals and toxic components. Utilizing residues and waste from agriculture and different industries is a novel trend in electrical and electronic applications [7]. According to Verma et al. [7], the utilization of residues and waste from agriculture and various industries is a new trend in electrical and electronic applications. This research provides an overview of works related to waste recycling, including red mud, ground rubber, tea waste, luggage, peanut, and hazelnut shells (agricultural waste), waste paper, polyethylene, and other various wastes in the production of highly effective materials for protection against electromagnetic (EM) interference. Very effective results have been recorded for agricultural waste, showing a reflection loss of up to −87.117 dB (ranging from 0.01 to 20 GHz). There are studies on the use of several agricultural residues, which are used as the basis for making absorber structures, such as wheat straw [8–11], rice residues [12–15], sorghum straw [16,17], cotton stalk [11], banana and coconut residues [5,18], etc. Research conducted by Ma et al. [8] presents new material for protection against EM radiation based on biological principles. In this research, new arrays of hollow porous carbon tubes (SCA) produced by the direct carbonization of wheat straw for the purpose of protecting against electromagnetic radiation were made and presented. Due to high EM reflection, conductive dissipation, and internal multiple reflections, these materials achieve a high level of shielding efficiency (SE) of 57.7 to 44.0 dB. Bai et al. in paper [9] show the straw carbon (SC)-enhanced electromagnetic shielding performance. The average shielding efficiency SE value of SC-900 °C was 16.79 dB with a 2.0 mm thickness, increasing to 47.58 dB with a 5.0 mm thickness. In the work of Aslam et al. [10], foam-like bio-carbon was obtained from wheat straw waste, and its microwave absorption capacity was studied.

Khalid et al., in their study [11], synthesized carbon nanoinerts via the pyrolysis of agricultural waste (in the form of wheat straw and cotton stalks) at a temperature of 500 °C and connected them into a cement matrix to improve its fracture characteristics and the effectiveness of shielding against electromagnetic radiation. Shielding efficiency was measured at a frequency range of 8–12 GHz: a maximum improvement of 23.5 dB with the intrusion of carbonized wheat straw and 22.9 dB with the intrusion of carbonized cotton stalk nanoparticles was gained. Rahmat et al., in paper [12], presented an examination of the efficiency of the rice husk and burned rice husk as a material that absorbs microwaves in the frequency range from 2 GHz to 4 GHz via the free space measurement method and simulation calculation using CST. According to the findings of Wee et al. [13], the dielectric properties of various agricultural waste materials at microwave frequencies were determined by measurements. In addition, the S parameters (S11 and S12) of these materials were measured at microwave frequencies (in the range from 2.2 to 3.3 GHz). Nornikman et al. in paper [14] present the design of a pyramidal microwave absorber made of rice husks and show how they are effective for operation in the frequency range of 1 GHz to 20 GHz. In a paper by Iqbal et al. [15], lightweight absorbers are designed that dampen electromagnetic waves in the frequency range from 4 GHz to 20 GHz. Two waste materials were used for the performance: rice husks and waste rubber (tire dust). The highest values of the attenuation constant of the EM wave absorber from rice husks is 65% at a frequency of 19 GHz, and from rubber powder is 87% at a frequency of 19.5 GHz. In paper [16], Xu et al. formed composites made from the remains of agricultural sorghum straw (SS), high-density polyethylene (HDPE), and carbon black nanoparticles (CB), which showed high EM protection with a shielding efficiency of 22.5 dB. Yin et al., in their paper [17], formed a hybrid obtained from regenerated sorghum straw/(Fe, Ni) using the calcination process. This hybrid exhibits excellent electromagnetic absorption at low frequencies with a maximum amount of −44.18 dB (frequency range from 0.17 to 0.99 GHz). Salleh et al., in their paper [18], represent a single-layer material that can be used as an absorber of EM radiation. This material is made from coconut shell-based activated carbon, where the 9.6mm sample has a minimum reflection loss of −17dB at 11.3 GHz. Due to their rich carbon source, which shows high shielding potential, agricultural residues are important materials that can be applied in manufacturing EM radiation absorbers [19,20]. However, the use of environmentally friendly biomaterials with potentially protective characteristics is still in its development phase, which is the reason for the significance of this research.

2. Shielding Efficiency

When an EM wave hits a material, part of the energy of the EM wave is reflected, part is absorbed, and the rest propagates through the material. The attenuation of an EM wave, when transmitted through a medium, is closely related to the energy absorbed in the medium through which that wave is transmitted. The power absorbed in a medium is obtained from the power balance between the incident power (P_{in}), the power reflected at the input interface (P_{ref}), and the power transmitted (P_t):

$$P_{ab} = P_{in} - P_{ref} - P_t \tag{1}$$

The reflected and transmitted power is simply determined using the measurements and simulation calculations of S parameters.

The scattering parameters Sij (or S-parameters) are complex values (phase and magnitude) and are characteristic of the device connected between the two ports. The S_{11} parameter corresponds to the power reflected at the input port of antenna 1 (Figure 1) and normalized to the incoming source power P_{in}:

$$|S_{11}|^2 = \frac{P_{ref}}{P_{in}} \tag{2}$$

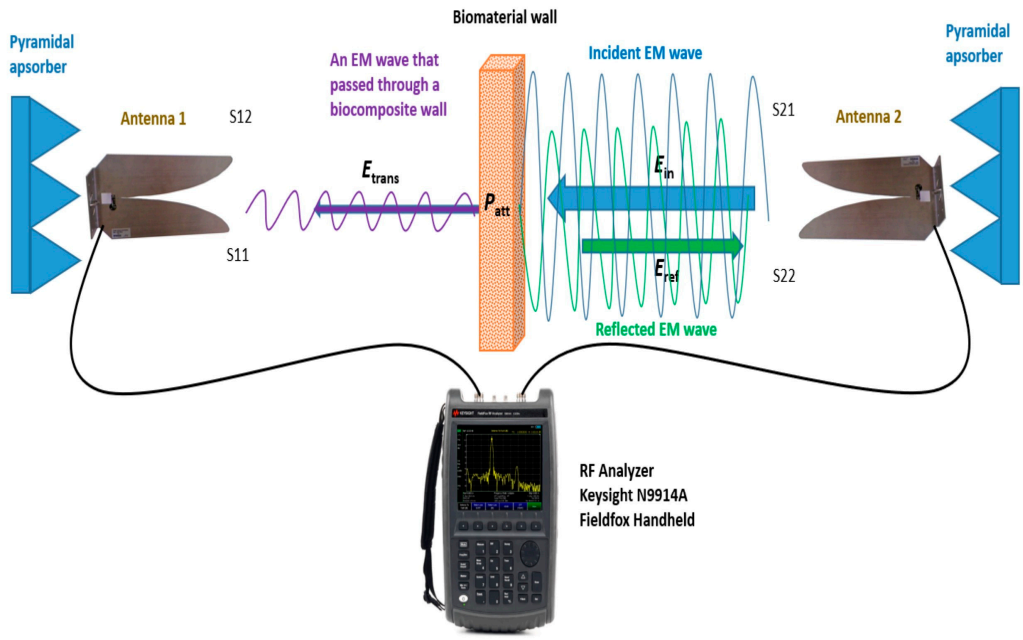


Figure 1. Scheme of measurement of EM wave transmission parameters S_{21} through harvest residues. Antennas 1 and 2 are identical UWB Vivaldi antennas with a gain of 14.7 dBI.

The S_{21} parameter corresponds to the power transmitted from antenna 1 to antenna 2, which is also normalized by the incoming power P_{in}:

$$|S_{21}|^2 = \frac{P_t}{P_{in}} \tag{3}$$

Absorption is defined as the ratio of the power absorbed by the material (P_{ab}) (Figure 1) to the input power and can be expressed as follows:

$$A = \frac{P_{ab}}{P_{in}} = 1 - |S_{11}|^2 - |S_{21}|^2 \tag{4}$$

The shielding efficiency of a building material is the measure of how much EM wave energy is reflected from that material and absorbed in the material. There is a decrease in the energy of that EM wave, and this decrease represents the attenuation of the EM wave.

SE quantifies the ability of the material to stop the transmission of the EM wave. The shielding efficiency of SE protection can be expressed as the ratio of the electric field, magnetic field, power, or, as used in this research, transmission parameters S_{21} (insertion loss) measured without protection (unshielded—ush) and with a shield (shield—sh), as indicated by the following equation:

$$SE_{s21} = 20log\frac{S_{21ush}}{S_{21sh}},\ \text{dB} \tag{5}$$

and also as follows:

$$SE = S_{21ush} - S_{21sh}\ ,\quad \text{dB} \tag{6}$$

All electrical devices are sources that generate EM waves in the space around them. The frequency range of these waves is from a few Hz to several hundreds of GHz. Arriving at a material, part of the wave is reflected, and part propagates into the material. If the material has a finite thickness at the exit from the material, an identical situation occurs; a part is reflected at the exit boundary, and a part is propagated across the boundary. If that material is a shield, we can discuss the EM wave that is reflected from the shield, the wave that propagates after the shield, and the part of the wave's energy that is absorbed in the shield material itself. The part of the wave that propagates after the shield is the focus of interest in this work, and the measurements were made based on that part of the EM wave. This part of the wave represents parameter S_{21}.

Access to protective shielding is possible in several ways, as shown in Figures 2 and 3. Namely, the space can be protected by a shield made of the biomaterial itself (Figure 1) or as a concrete (brick) biomaterial multi-layer structure (Figure 2).

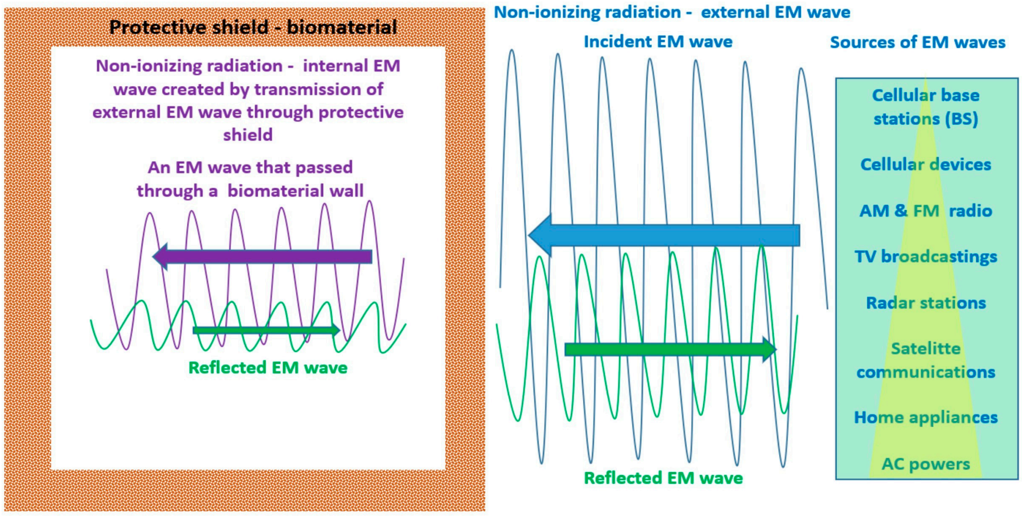


Figure 2. EM shielding—a basic method for protection against non-ionizing radiation.

Furthermore, the entire facility can be made of biomaterials or only rooms that are of greater importance (sleeping area, children's room, etc.), or as a combination of both approaches. Buildings made of straw and mud have existed in various parts of the world for thousands of years, and lately, they are starting to be rebuilt as a response to existing materials as ecological structures [21,22]. However, their influence on EM radiation has been neglected.

Objects built using biomaterials, in addition to their excellent thermal properties, also have the potential for EM protection, which is the topic of this research. In combination with clay (mud), such materials can significantly improve their thermal and probably also EM protective properties. The reason for this probability lies in the research on the EM transmission properties of clay and concrete materials [8,9], which shows that the maximum attenuation of the EM wave when passing through clay materials can range in parts of the spectrum (this research was carried out in the range from 80 MHz to 18 GHz) for up to 20 dB, and with concrete up to 40 dB. If compared to conductive metal shields, these results are inferior, but the key advantage of biomaterials is their low price, abundance, availability, usability, and recyclability.

The aim of this research was to employ harvest residues (soybean straw, wheat straw, and clover straw) that could also serve as an additional protection material in residential building construction as EM radiation absorbers. Because harvest residues are widely distributed, readily available by-products of harvest production, their application for this purpose is acceptable. The main goal of this work is to measure the transmission parameters of EM waves through chopped harvest residues and then to measure the absorption properties of those natural absorbers and their potential as the coverings of building structures to reduce EM pollution.

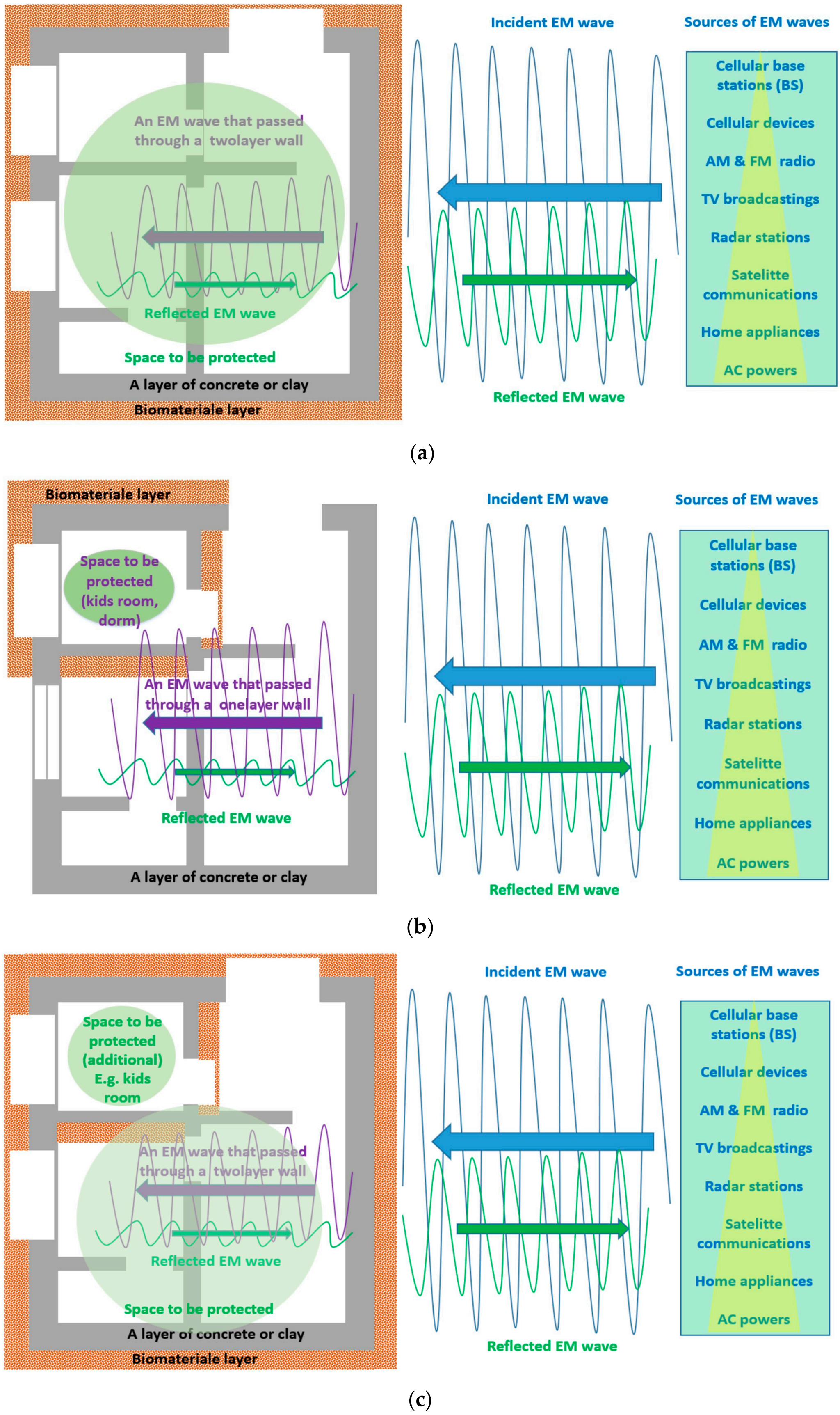


Figure 3. Floor plan of a building coated with a biomaterial protective layer: (**a**) completely coated from the outside; (**b**) only the room to be protected is coated; (**c**) the building is completely coated from the outside plus the room to be protected is coated.

3. Materials and Methods

The biological materials for which the absorption was measured refer to dried and chopped soybean straw, wheat straw, and large clovers (Figure 4). They were used as a bio-substrate of uniform mass through which the EM radiation of different frequencies was passed under controlled conditions. In addition to the dry substrate, moist absorbers were also used, which were made so that a certain amount of water could be added to the dry straw. Industrially produced composites form part of the measuring set-up while the measurement straws alternated inside the constructed housing. The constructed case was made as a wooden box with a movable PVC partition that could be placed at three distances from the last wooden panel of the box (at a distance of 100, 200, and 300 mm). In this way, three "plates" of biomaterials with a thickness of 100, 200, and 300 mm were made (Figure 5). These measurements are carried out by placing the PVC partition at a position 100 mm away from the back panel of the wooden box and filling it with 3.8 kg of the substrate, the measurement of which is carried out; and then the PVC partition is placed at a distance of 200 mm (and filled with 7.6 kg of the substrate) and the measurement is carried out; and finally, the partition is placed at a distance of 300 mm from the back panel of the wooden box (and filled with 11.4 kg of the substrate) and the measurement is carried out. In this way, three "panels" made of substrate thicknesses of 100, 200, and 300 mm and a density of 67.56 kg/m^3 were formed.

(**a**) (**b**) (**c**)

Figure 4. Tested biomaterials: (**a**) soybean straw; (**b**) wheat straw; (**c**) clover straw [23].

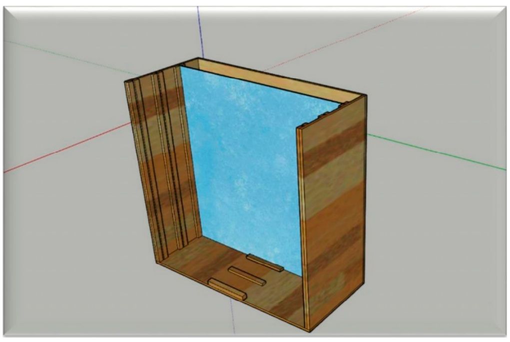


Figure 5. Wooden box (dimensions 750 × 750 × 300 mm) with a movable PVC partition made for forming biomaterial plates with a thickness of 100, 200, and 300 mm [10].

Measurements

The measurement of S_{21} transmission parameters was carried out in free space with two rows of pyramidal absorbers 600 × 600 mm (with nine pyramids 600 mm long) placed behind measuring antennas 1 and 2 in order to reduce the reflection from the surrounding walls (Figure 6).

Figure 6. Photo of measuring EM wave transmission parameters through biomaterial (wheat harvest residues) in a room with EM reverberation using two Vivaldi antennas: the UWB-2, RFSPACE, Atlanta; GA, USA and RF Analyzer, Fieldfox Handheld N9914A, KEYSIGHT, Santa Rosa, CA, USA [23].

The measuring space was not EM-isolated. Since three types of material and three thicknesses of material were provided for the two moisture conditions, dry and wet (with three levels of humidity), the following measurements were performed:

(a) The transmission coefficient S_{21} for three types of dry samples is shown below:
- 100 mm: soybean straw, wheat straw, and clover straw;
- 200 mm: soybean straw, wheat straw, and clover straw;
- 300 mm: soybean straw, wheat straw, and clover straw.

(b) The transmission coefficient S_{21} for three types of wet samples is shown below:
- 300 mm: soybean straw, wheat straw, and clover straw (humidity 8.06%);
- 300 mm: soybean straw, wheat straw, and clover straw (humidity 14.93%);
- 300 mm: soybean straw, wheat straw, and clover straw (humidity 34.48%).

Measurements of the transmission coefficients of S_{21} were carried out in two basic experiments, with dry and wet materials, with three thicknesses of the biomaterial board layer at 100, 200, and 300 mm. The measurement of transmission parameters was performed using an RF analyzer N9914A FieldFox Handheld (300 kHz to 6.5 GHz), with two Vivaldi antennas UWB-2 (fmax: 6 GHz, 15.7 gain dBI; Figure 1). The measurements were carried out in the range of 300 MHz–5 GHz, which includes most of today's communication and broadcasting systems (from 2G–5G mobile telephony, FM radio, WIFI, WLAN, DVBT2, and others). Thus, the most common way to determine the SE is by measuring the transmission parameters S_{21} (or S_{12} parameters). In such a measurement, in addition to the transmission parameters, the reflection parameters (S_{11} and S_{22}) are also measured because they can give us information about the part the EM wave energy plays that is reflected on the shield (Figures 1–3) [24,25]. An EM shield made of material that has high reflection and low transmission is a shield that provides high protection against EM radiation.

4. Results and Discussion

The measurement results are presented in Figures 7 and 8, whereas the calculated SE parameter is shown in Figures 9 and 10. The measurement results for individual samples (three thicknesses) show S_{21} parameters measured in a wooden box, so they also affected the transmission of the EM wave when passing through them. Therefore, the boxes' measurements were carried out separately and shown on each diagram (box frame) (Figure 7).

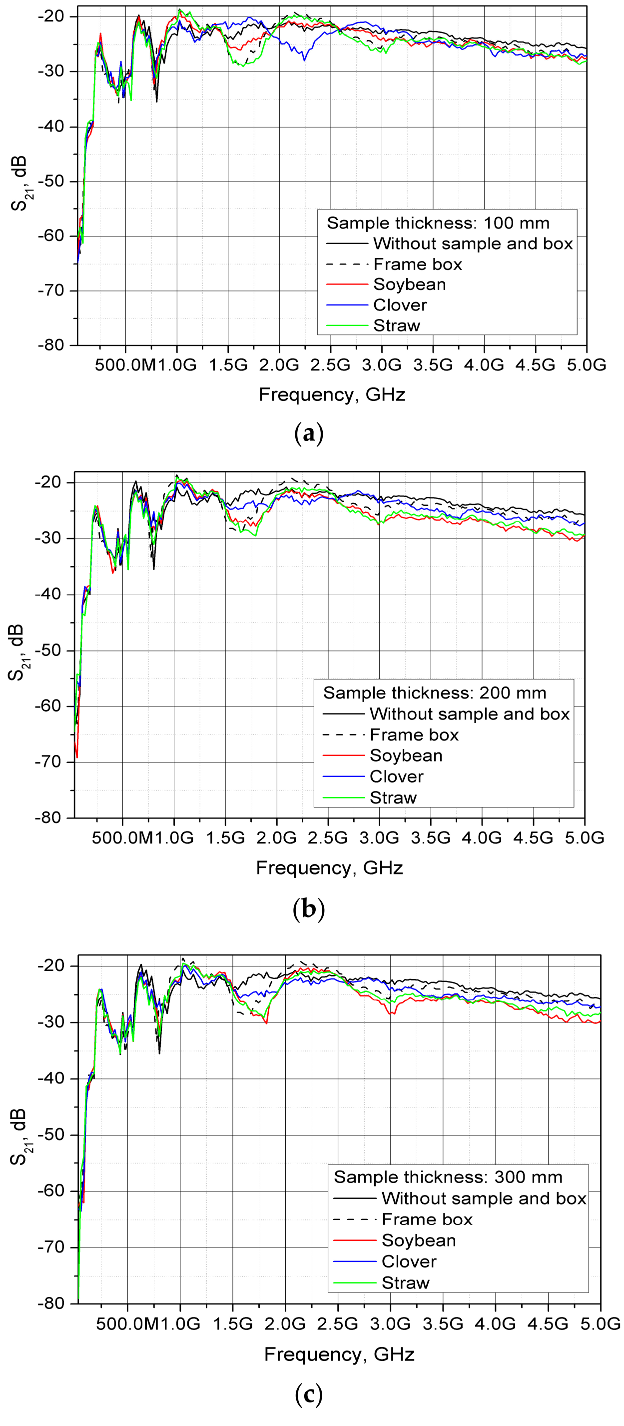
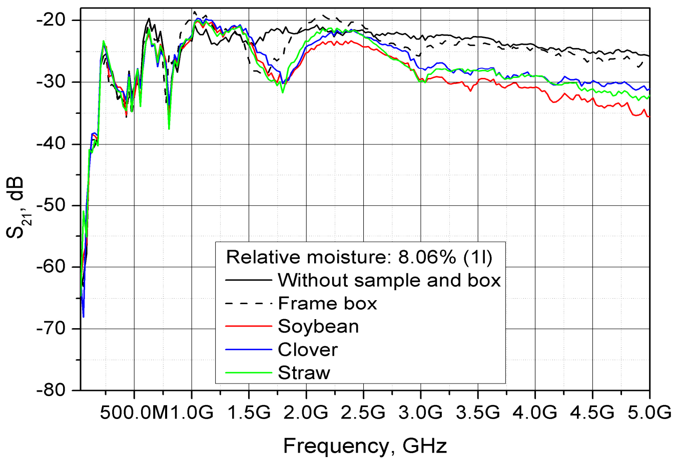
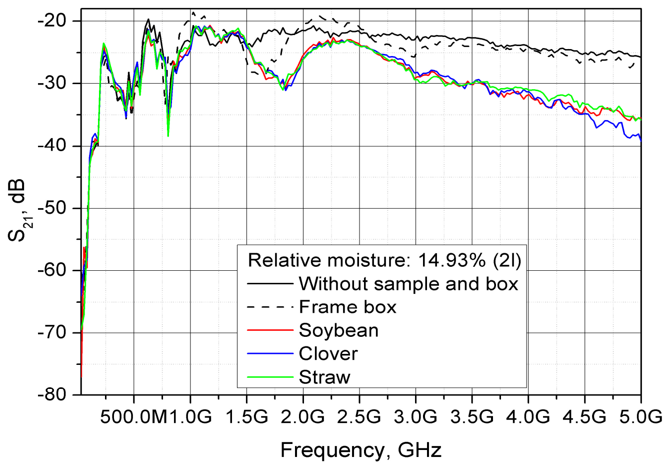


Figure 7. Measured S_{21} parameters of dry straw thickness samples: (**a**) 100 mm; (**b**) 200 mm, and (**c**) 300 mm (relative moisture < 5%).



(**a**)



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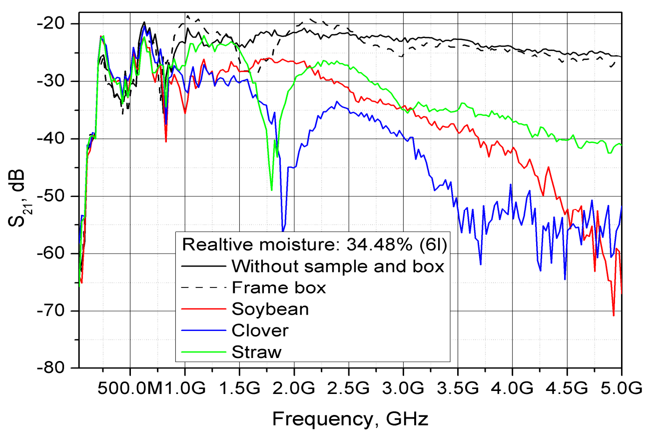
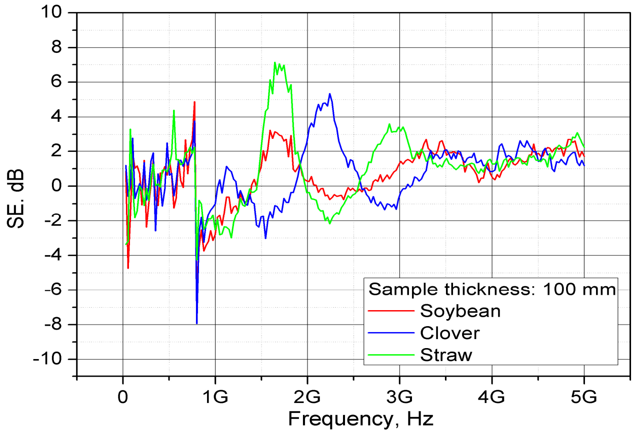
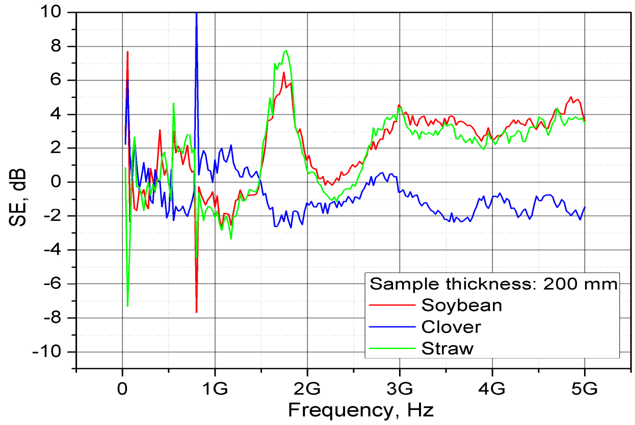


(**c**)

Figure 8. Calculated S_{21} parameters of wet soybean straw, wheat straw, and clover straw samples of relative humidity: (**a**) 8.06%; (**b**) 14.93%, and (**c**) 34.48% (sample thickness 300 mm).



(**a**)



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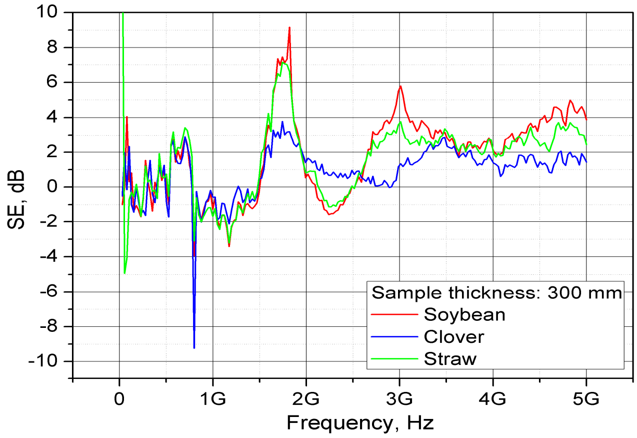

(**c**)

Figure 9. Calculated SE of dry soybean straw, wheat straw, and clover straw samples of varying thickness: (**a**) 100 mm; (**b**) 200 mm, and (**c**) 300 mm (relative moisture < 5%).

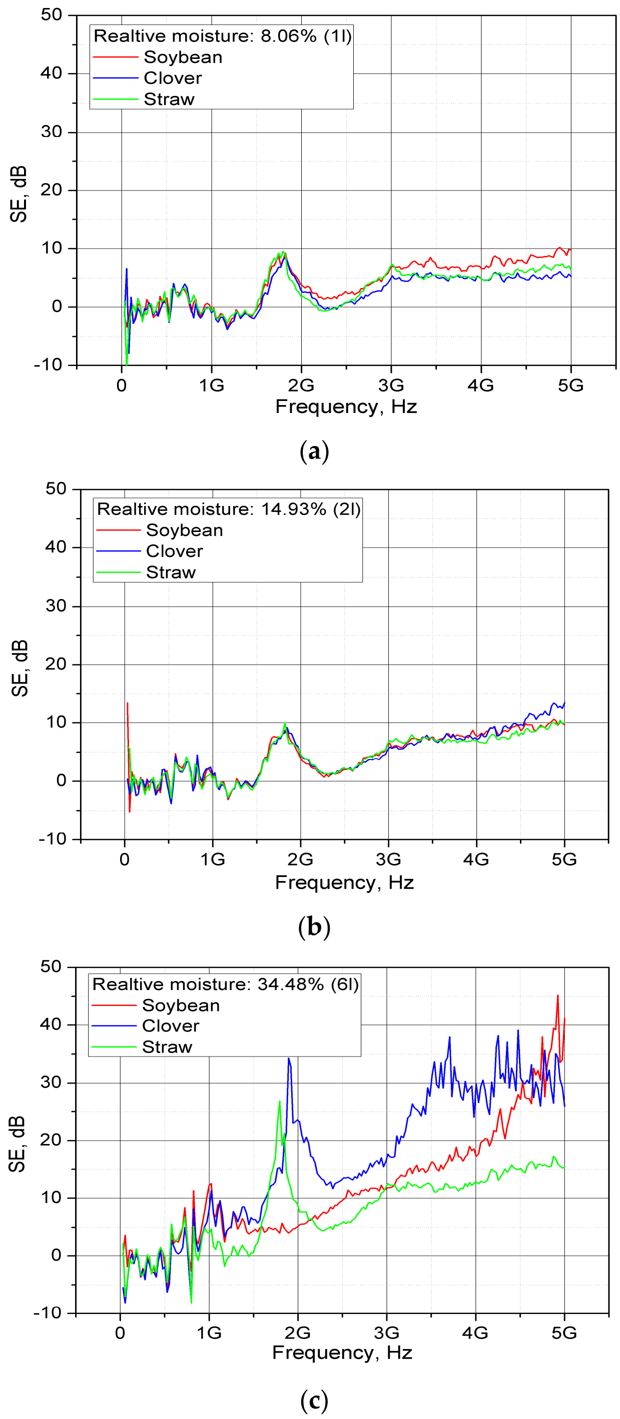

Figure 10. Measured SE of soybean straw, wheat straw, and clover straw samples at various levels of relative humidity: (**a**) 8.06%; (**b**) 14.93%, and (**c**) 34.48% (sample thickness 300 mm).

In the range above 700 MHz, different EM wave transmissions through the samples occurred for different sample thicknesses. Namely, for a sample thickness of 100 mm in the range from 700 MHz to 1.3 GHz, the lowest values of the transmission parameter were shown in clover straw samples with a minimum value of −25 dB at a frequency of 1.2 GHz. In the following range from 1.3 to 1.8 GHz, the lowest values of the transmission parameter are shown by the wheat straw sample with a minimum value of −28 dB at the frequency of 1.63 GHz. In the range from 1.8 to 2.59 GHz, the lowest value of the transmission parameter is shown by the clover straw sample, with the lowest value of −27.5 dB at the frequency of 2.25 GHz. In the range from 2.59 to 3.25 GHz, the lowest value of the transmission parameter was measured with the wheat straw sample at the amount of −26.0 dB and at the frequency of 3.00 GHz (Table 1). In the rest of the measured frequency range, there was no significant difference in the measured transmission parameters for different samples (Figure 7).

Table 1. The lowest measurement of the value of the transmission parameter S_{21} of dry samples for three thicknesses: 100, 200 and 300 mm.

Samples	Sample Thickness (mm)	Frequency (MHz)	S_{21} (dB)
Straw	100	1.63	−28.0
Soybean	200	4.93	−30.5
Soybean	300	1.82	−30.2

For dry samples up to a frequency of 700 MHz, there were no significant differences in the transmission parameters for different samples and for different sample thicknesses. By increasing the thickness of the sample, the measured values of the transmission parameter S_{21} were further reduced. However, this difference was visible at the highest frequencies of the measured range. Thus, for a sample with a thickness of 200 mm at a frequency of 4.7 GHz, the difference between the S_{21} parameter measured in the frame box and the soybean straw sample was −3.1 dB, and for a sample with a thickness of 300 mm it was −3.2 dB at the same frequency (for a sample thickness of 100 mm, the difference, was −0.9 dB at a frequency of 4.7 GHz). For a sample thickness of 200 mm, the soybean straw sample showed the lowest transmission parameter values in the frequency range above 3.00 GHz, while below that frequency (and above 700 MHz, where there is no difference), the difference between the transmission parameter of the soybean straw and wheat straw samples was below 1.50 dB. The lowest measured value of the transmission parameter for a thickness of 200 mm (above 700 MHz) was −30.45 dB at a frequency of 4.93 GHz (for soybean). For a sample thickness of 300 mm, significant differences in transmission parameters appeared above 1.5 GHz (except in the range from 2.00 to 2.65 GHz, where the dominant clover straw sample was the lowest S_{21}), and the lowest transmission parameter values were shown in the soybean straw sample. The lowest measured value of the transmission parameter for a thickness of 300 mm (above 700 MHz) was −30.19 dB at a frequency of 1.82 GHz (for soybean).

The results presented in Figure 8 show measured comparative diagrams by types of samples (on each diagram) with different humidity levels (same thickness: 300 mm). Comparisons of the same sample with different thicknesses and humidity levels were omitted due to the excessive number of figures (Figure 8).

Besides the thickness of the sample, another important factor is the moisture in the sample, which significantly affects the transmission of the EM wave through the sample. The reason for this lies in the increase in the electrical conductivity of the sample, which increases the reflection and decreases the transmission. This influence of sample moisture on transmission was more significant than the influence of sample thickness for the sample densities that were measured.

Due to the increase in the moisture of the sample, the transmission parameter of the EM wave through the sample dropped to the value of −35.55 dB (the difference was according to the box frame of −9.1 dB) for a soybean straw sample with a moisture content of 8.06% at a frequency of 5.00 GHz; −39.23 dB (the difference was according to the box frame of −12.78 dB) for a clover straw sample with moisture content of 14.93% at a frequency of 5.00 GHz; and −70.80 dB (the difference was according to a box frame of −43.80 dB) for a soybean straw sample with a moisture content of 34.48% at the frequency of 4.93 GHz (Table 2). The thickness of all wet measured samples was 300 mm. For the lowest amount of moisture in the samples (8.06%), the lowest values of the transmission parameters in the entire measurement range (above 700 MHz) were shown by the soybean straw sample; for the middle level of moisture (14.93%) there was no significant difference in the values of the transmission parameters between samples. For the highest amount of moisture (34.48%), the lowest values of the transmission parameters are shown in the clover straw sample.

Table 2. The lowest measurement of the value of the transmission parameter S_{21} for wet samples at three relative moisture levels: 8.06, 14.93 and 34.48%.

Samples	Relative Moisture (%)	Frequency (MHz)	S_{21} (dB)
Soybean	8.06	5.0	−35.55
Clover	14.93	5.0	−39.23
Soybean	34.48	4.93	−70.80

According to the criterion of the lowest values of transmission parameters in the entire measurement range for the highest amount of moisture, the clover straw sample showed the most favorable results (the lowest value of −65.00 dB at the frequency of 4.5 GHz), followed by soybean straw and wheat straw. The mean value of the transmission parameter of the measured range (from 700 MHz to 4.63 GHz) for clover straw was −42.62 dB, for soybean straw −40.88 dB, and −35.20 dB for wheat straw. In addition to the two mentioned parameters (thickness of the sample and moisture) of the material, the transmission was also affected by the density of the sample (kg/m^3). The sample material's permittivity was closely related to this. Namely, by increasing the density of the sample, the permittivity also increased and, therefore, the transmission of EM wave energy through the sample decreased. Permittivity indicates the intensity of the polarization of the material via electric fields and is defined as the ratio of the density of the electric current in the material to the strength of the electric field in a vacuum. The density of a material is a measure of the mass per unit volume of a substance. The measured samples' density is relatively low (67.56 kg/m^3), so by increasing the density, these relatively poor transmission results, particularly of dry samples, can be significantly improved. This was not examined in this paper but remains for future research to follow. The shielding efficiencies increase with the increase in the sample thickness in dry samples. For dry samples, the highest SE of 10.36 dB was achieved at a frequency of 0.8 GHz (Figure 9b) for the clover straw (200 mm) (Table 3).

Table 3. The highest measured values of the shielding efficiencies SE of dry samples at three thicknesses of 100, 200 and 300 mm.

Samples	Sample Thickness (mm)	Frequency (MHz)	SE (dB)
Soybean	100	1.61	7.10
Clover	200	0.80	10.36
Straw	300	1.80	9.20

The highest SE of 45 dB at a frequency of 4.9 GHz was reached for the soybean straw sample with the highest humidity (34.48%). However, in the entire frequency range (Figure 10c), the clover straw showed the highest SE values (Table 4).

Table 4. The highest measured values of the shielding efficiencies SE of dry samples and wet samples at three relative moisture levels of 8.06, 14.93 and 34.48%.

Samples	Relative Moisture (%)	Frequency (MHz)	SE (dB)
Soybean	8.06	4.90	10.08
Clover	14.93	4.80	10.30
Soybean	34.48	4.90	45.00

The differences in the transmission parameter in the dry samples were not significant in the entire measured range, but in wet samples (especially at the highest humidity of 34.48%), the clover straw sample stood out, showing a significant decrease in the transmission parameter in the entire measured range. If these results are looked at from the point of view of the shielding efficiency of the SE, it can be seen that soybean straw and clover are the samples with significantly higher SE values for the dry samples, especially at two higher sample thicknesses (200 and 300 mm; Figure 9b,c). However, in wet samples (for the highest humidity), clover straw has a significantly higher value of shelling efficiency than the other two samples for a measured thickness of 300 mm (Figure 10c).

5. Conclusions

This paper deals with the application of crop residues as absorbers of EM energy in a wide frequency range. For this purpose, plate absorbers were made from the remains of clover, soybean, and wheat straw, and measurements of the transmission parameters were carried out, from which the values of the SE armoring efficiency were calculated. The purpose of these measurements was to determine the potential of these harvest residues as material for the production of coverings that could cover residential buildings or with which residential buildings could be built with a high level of protection against EM radiation. The measurement of S_{21} transmission parameters was carried out in a space that was not EM-isolated at a frequency range from 300 MHz to 5 GHz. The parameters of the measured samples that were examined included the sample type, sample thickness (100 mm (weight 3.8 kg), 200 mm (weight 7.6 kg), 300 mm (weight 11.4 kg), and humidity (8.06%, 14.93% and 34.48%). It is evident from the measurement results that the transmission parameters of S_{21} decreased with the increase in the sample thickness, humidity, and frequency. Therefore, by increasing the thickness of the sample, the transmission of the EM wave through each of the samples decreased, and the lowest level of the transmission parameter in the dry sample was shown by soybean straw, which was −30.5 dB at 4.93 GHz (at a thickness of 200 mm). This was also the case for the important sample with the highest humidity of 34.48% in the form of soybean straw and was −70.8 at the same frequency as the dry sample. The values of the shielding effectiveness of the SE show that although the clover has the highest value of 10.98 at 0.8 GHz at greater thicknesses of soybean and wheat straw, it has high values for this parameter throughout the measurement range (the highest value is 9.2 dB at a frequency of 1.9 GHz at a thickness of 300 mm of wheat straw). With wet samples, the difference in SE samples is visible only at the highest humidity (34.48%), and the highest SE value is shown by soybean straw at the amount of 45dB and at the frequency of 4.9 GHz. An analysis of the entire measured range for moist samples shows the significantly higher SE values of the clover straw sample for the highest substrate moisture. The density of all measured samples of 67.56 kg/m^3 is relatively low, and therefore, the differences between individual thicknesses and types of samples are small. Increasing the density of the samples could have a significant impact on the transmission of the EM wave through the material. In addition, the tests were conducted on samples that were not additionally processed, which leaves room for optimization and further research into the field of EM wave transmission through biomaterials from harvest residues. Biomaterials have the potential to protect against EM radiation and, thus, as they also served in the past, they again become the basis for the construction of buildings with a reduced level of EM radiation in the future.

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