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REGULAR ARTICLE

Fabrication of Bio-Polymer Nanocomposite EMI Shields Based on Sugarcane Bagasse and PVA/PANI/MWCNT, and Evaluation of the Shielding Effectiveness in Relation to the Various Compositions

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In the present research, conductive polymer bio composite thin shields consisting of polyvinyl alcohol (PVA), poly aniline (PANI)-conductive polymer, multi-walled carbon nanotubes (MWCNT) and sugarcane bagasse (SB) biochar are fabricated and compared. The pyrolysis technique is employed for producing biochar. To develop several kinds of bio composite shields, PANI, MWCNT, and SB bio char were mixed with PVA using a magnetic stirrer. PVA and PANI compositions of 10g and 2g were fixed, respectively. Four shield samples (SB1, SB2, SB3, and SB4) were fabricated by altering the MWCNT and SB composition. Using the Van der Pauw approach, the conductivities of the shields were estimated to be 6.44, 21.88, 25.86, and 35.04 S/m, respectively. Shielding effectiveness (SE) and S-parameters were computed using the microwave test bench method in the X band at a frequency of 10 GHz. To determine SE and acquire S-parameters, simulations were run in the CST microwave studio simulator. Sample SB4 shield had the maximum SE of 40 dB (experimental) and 42 dB (simulated) at 1 mm thickness, subsequently, a comparison and explanation of the experimental and simulated data are shown. The combination of filler materials PANI and MWCNT is a novel choice which has increased the SE of the SB bio char. This is attributed to the higher conductivity and better aspect ratio of sugarcane bagasse bio char, which facilitates the formation of a conductive network on the shield's surface. Thus, the proposed novel combination of materials gives high SE for a very thin film. Utilizing abundant sugarcane bagasse waste for EMI shield fabrication not only reduces electromagnetic pollution but also contributes to mitigating environmental pollution.

Keywords: Bio char, Bio-polymer nanocomposites, Electromagnetic interference, Shielding effectiveness, S-parameters.

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1. INTRODUCTION

Microwave radiation is a major hazard to human health and electronic devices in the quickly expanding fields of electronics, communication, wireless technology, radar and detecting equipment [1]. Various microwave absorbers using different compositions and structures have been developed to counteract these effects. The shape, size, and dispersion of these materials' constituents affect their effective permittivity and impedance matching, which in turn affects their absorption efficiency [2]. Consumer demand needs that future-generation microwave absorbers to be thin, lightweight, flexible, and able to absorb electromagnetic (EM) waves with high performance and broad range [3]. Because of their high aspect ratios, low weight, better corrosion resistance and exceptional electrical conductivity, carbon-based fillers – such as carbon nanofibers, graphene, and carbon nanotubes – have become more well-known among the materials being studied [4]. One significant issue with carbon fillers, though, is that they have a propensity to group together, which reduces their capacity to absorb microwave radiation [5]. New investigations have focused on creating flexible nanocomposites that incorporate lightweight multi-walled carbon nanotubes (MWCNTs), polyaniline and biochar made from sugarcane bagasse. These nanocomposites are then embedded in a polyvinyl alcohol (PVA) matrix using a straightforward solution-casting method in order to overcome this constraint. These novel materials maintain their thinness, light weight, and flexibility while achieving notable X-band microwave absorption. This technique is feasible for real-world applications because, in contrast to conventional methods, it lowers filler loading while preserving excellent absorption efficiency. The shielding effectiveness (SE) is commonly measured in terms of the logarithmic ratio of the incident power on the shield to the

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transmittance power through the shield. Mathematically, it can be shown as equation (1) [6].

$$SE\ (dB) = 10 \log(P_i/P_t) = 20 \log(H_i/H_t) = 20 \log(E_i/E_t) \quad (1)$$

When an EM wave strikes on a shield material, the well-known phenomenon of reflection, absorption and transmission takes place. Reflection is due to a mismatch of the medium impedance at the surface of the shield material. Some part of the EM wave is absorbed by the shield material while the remaining part is transmitted. Apart from these phenomena, multiple reflections inside the shield also occur. Therefore, the resultant shielding effectiveness of a shield material (SE_T) depends on absorption (SE_A), the reflection (SE_R), and multiple reflections (SE_M) in the shields and is given by the following relation [7, 8].

$$SE_T = SE_R + SE_A + SE_M \quad (2)$$

If the absorption loss (SE_A) is greater than 10 dB, the multiple reflection term can be disregarded. S_{11} parameter (Reflection loss) and S_{21} parameter (Transmission loss or SE) can be measured using Vector Network Analyser (VNA) as a tool. The following equations (3) to (5) provide the relationships between the power coefficients of transmittance (T), absorption (A), and reflection (R) [9, 10]:

$$\text{Reflection (R)} = (S_{11})^2 = (S_{22})^2 \quad (3)$$

$$\text{Transmittance (T)} = (S_{12})^2 = (S_{21})^2 \quad (4)$$

$$\text{Absorption (A)} = 1 - T - R \quad (5)$$

In terms of power coefficients, the shielding efficiency of the shield materials due to reflection and absorption can be given by equations (6) to (8).

$$SE_R = 10 \log (1/ (1-R)) \quad (6)$$

$$SE_A = 10 \log ((1-R)/T) \quad (7)$$

$$SE_T = 10 \log (1/T) \quad (8)$$

According to EMC regulations a SE of at least 40 dB is required to deliver the shielding of 99.99 % of EMI radiation for most of the important applications. Around 30 dB of SE is acceptable for most industrial and consumer applications.

2. MATERIALS AND FABRICATION

Poly aniline is used as a polymer matrix. Its pellet density is 1.2 – 1.4 g/cm^3 and electrical conductivity is 1 – 5 S/cm. MWCNTs with purity > 99% have their inner diameter, outer diameter and length as ~ 2 – 6 nm, ~ 10 – 15 nm and 0.1 – 10 micron respectively. They have density of 0.06 – 0.09 g/cm^3 and electrical conductivity is specified as 10^6 S/m. Bio char of sugarcane bagasse was prepared by pyrolysis process. Polyvinyl alcohol (PVA) is used as hardener and its density and molecular weight were 1.19 g/cm^3 and 145,000 respectively.

2.1 Preparation of Bio Char from Biomass

In order to produce high-quality biochar, necessary biomass of clean and dry sugarcane bagasse (Fig. 1(a)) was gathered from the neighbourhood and pyrolyzed without delignifying the biomass in an electric muffle furnace set to 500 °C with a heating rate of 10 °C per minute for an hour. After allowing the biochar to cool to ambient temperature, it was sieved, pounded into a powder and placed in airtight containers labelled appropriately.

a b

Fig. 1 – (a) Biomass of sugarcane bagasse (b) Biochar of sugarcane bagass

2.2 Fabrication Process

PANI (2g), Bio char of Sugarcane bagasse (2g) and MWCNT (1g) were mixed manually to form composite powder (5g). This mixture was mixed with 100 ml of Distilled water and 10g of PVA to make colloidal solution with the help of magnetic stirrer at 70°C temperature. The stirring was done at 400 rpm for 4 hours. The solvent casting method used for the formation of shields. The colloidal solution was poured on cellulose sheet or dried on the flat surface and was kept for drying at room temperature for one day so that distilled water can evaporate. To analyze the effect of % wt. of bio char and MWCNT, weight of PANI and PVA was fixed as 2g and 10g respectively in all four experiments and weights of bio char and MWCNT were varied and four different bio composite shields were fabricated (Fig. 2) and designated as SB1, SB2, SB3 and SB4. The composition of all shields is summarized in Table 1.

a b c d

Fig. 2 – Fabricated CPBC shields of Sugarcane bagasse (a) SB1 (b) SB2 (c) SB3 (d) SB4

3. EMI SHIELDING AND S-PARAMETER MEASUREMENT

3.1 S-parameters measurement using microwave test bench

For the S-parameters (S_{11} and S_{21}) measurement, klystron oscillator-based microwave test bench designed for X band was used. For the tuning of the system, beam voltage $V_B = 205$ V, repeller voltage $V_R = -95$ V, beam current $I_B = 15$ mA and frequency of input microwave – 10 GHz was set up. Two identical Horn antennas were used for the transmission and reception of microwaves. Input power of –30 dB was applied to the transmitting antenna and the output powers received by receiving antenna were recorded from VSWR/power meter connected to it. The experimental setups for S_{21} parameter and S_{11} parameter measurements are shown in Fig. 3 respectively.

Table 1 – Compositions of different CPBC shields of sugarcane bag

CPBC shield	PVA (gm)	PANI (gm)	Bio char (gm)	MWCNT (gm)	Total wt. (gm)
SB1	10	2	2	1	15
SB2	10	2	3.5	2	17.5
SB3	10	2	5	2	19
SB4	10	2	3.5	3	18.5

a b

Fig. 3 – (a)Experimental setup of klystron microwave test bench for S_{21} measurement, (b) Experimental setup of klystron microwave test bench for S_{11} measurement

For the S_{21} measurement, EMI shields were placed in between two horn antennas facing each other, whereas for S_{11} measurement, EMI shields were kept in front of two horn antennas, both facing same side. The input power Pi (dB), output power Pt (dB) in S_{21} mode and output power Pr (dB) in S_{11} mode for all four shields were noted and S-parameters were calculated using following equations,

$$S_{21}\ (\text{dB}) = \text{Pt} - \text{Pi} \tag{9}$$

$$S_{11}\ (\text{dB}) = \text{Pr} - \text{Pi} \tag{10}$$

From S-parameters SE_R, SE_A, SE_T were calculated with the help of equations (3) to (8). The determined values of Reflection (R), Absorption (A), Transmittance (T), Shielding Effectiveness SE_R, SE_A and SE_T for different types of shields are summarized in Table 2. It can be observed that as fillers (bio char and MWCNT) composition increases, total shielding effectiveness SE_T increases.

Table 2 – Summary of shielding effectiveness for different shields

CPBC shield	R	A	T	SE_R (dB)	SE_A (dB)	SE_T (dB)
SB1	0.0001	0.9683	0.0316	0.0043	14.9956	15
SB2	0.0158	0.9832	0.0010	0.0692	29.9308	30
SB3	0.0457	0.9537	0.0006	0.1966	31.8034	32
SB4	0.1000	0.8999	0.0001	0.4576	39.5424	40

3.2 Calculating the Conductivity of Shields Using Van der Pauw Technique (Four Probe Method)

The Van der Pauw technique's four probe method, which uses a Gauss meter and operates on the Hall effect concept, can be used to estimate the sheet resistance R_S, resistivity, and conductivity [11, 12]. The Van der Pauw method's experimental setup is depicted in Fig. 4. Van der Pauw technique is popular methodology for determining the electrical conductivity or sheet resistance of thin films, including EMI shielding materials. The shield sample need to be a uniformly thin, flat layer and have a simple shape, such as a circle or rectangle. At the corners or borders of the shield sample, make four tiny ohmic connections in order to prevent the measurement from being disturbed. This set up usually uses a voltmeter and a source meter (current source). In one configuration, the voltage and current were measured in two orders. Voltage V_{34} between contacts 3 and 4 was measured after injecting current I_{12} through contacts 1 and 2 then the following equation (11) was used to get the resistance.

$$R_{(12,34)} = I_{12}/V_{34} \tag{11}$$

Then, for the other case, the reverse configuration, reverse current I_{21} was injected through contacts 2 and 1 and the voltage V_{43} between contacts 4 and 3 was measured and the reverse resistance was calculated from the equation (12)

$$R_{(21,43)} = V_{43}/I_{21} \tag{12}$$

For the perpendicular configuration, the procedure was repeated. Using the abovementioned equations, the resistances $R_{(23,41)}$ and $R_{(32,14)}$ were computed after injecting current I_{23} through contacts 2 and 3 and measuring V_{41} between contacts 4 and 1. The Van der Pauw formula (13) was used to determine sheet resistance:

$$\exp(-\pi R\text{s}/R_A) + \exp(-\pi R\text{s}/R_B) = 1 \tag{13}$$

Where:

$$R_A = R_{12,34} + R_{21,43}$$

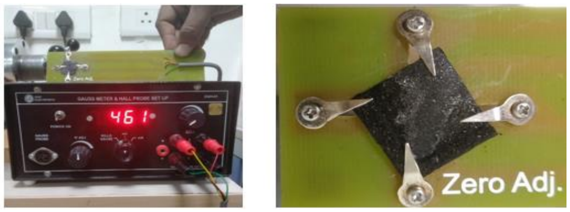
$$R_B = R_{23,41} + R_{32,14}$$

Rs is the sheet resistance.

Numerical methods (e.g., iteration) can solve for Rs. If the thickness (t) of the sample is known then the conductivity (σ) can be obtained from the following equation (14). Resistivity is inverse of conductivity.

$$\sigma = 1/(R\text{s.t}) \tag{14}$$

In these experiments, the shields of area 1 cm x 1 cm and thickness of 1 mm were used. It can be seen that as fillers' content increases, conductivity increases and the estimated data is summarised in Table 3.



a b

Fig. 4 – Experimental setup of a rectangular Van der Pauw configuration

Table 3 – Summary of R_s, ρ and σ for different types of EMI shields

CPBC shield	R_S (Ω)	ρ (Ω.cm)	σ (S / m)
SB1	155.24	15.52	6.44
SB2	47.2	4.72	21.88
SB3	38.7	3.87	25.86
SB4	28.54	2.854	35.04

4. MODELLING AND SIMULATIONS

The thin films SB1-SB4 formed from sugarcane bagasse were physically modelled in CST MW studio simulator. It was placed in the centre of a rectangular waveguide with conventional dimensions of a = 22.86 mm (0.9 in) and b = 10.16 mm (0.4 in). Two ports were designated at either end of the waveguide, and its length of 100 mm was chosen. The frequency range chosen was 8 GHz to 12 GHz (X band), and port 1 was excited with 1 W of power in TE_{10} mode. S parameters were recorded at 10 GHz while simulations were conducted in time domain mode. The simulator's material library defines the composite material for thin film, which has the following properties: relative permeability $\mu_r = 1$, conductivity σ = 6.44, 21.88, 25.86, and 35.04 S/m, and relative permittivity $\epsilon_r = 3$ (averaged for 25 % wt to 75 % wt of biochar in CPBC at 10 GHz). Thickness of film was selected as 1 mm. Equations (3) through (8) were used to compute the shielding effectiveness SE(R), SE(A) and SE(T) based on the S parameter data. The results in the form of S_{21} and S_{11} parameters for the different shields of Sugarcane bagasse are shown in Figs. 5 and 6 respectively. The simulated values of S-parameters at 10 GHz and calculated values of shielding effectiveness of these shields are summarized in Table 4.

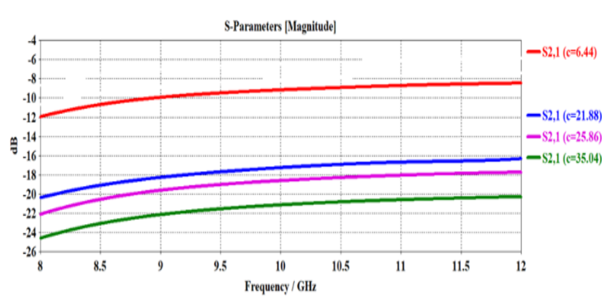


Fig. 5 – S_{21} parameter of thin film of CPBC shield

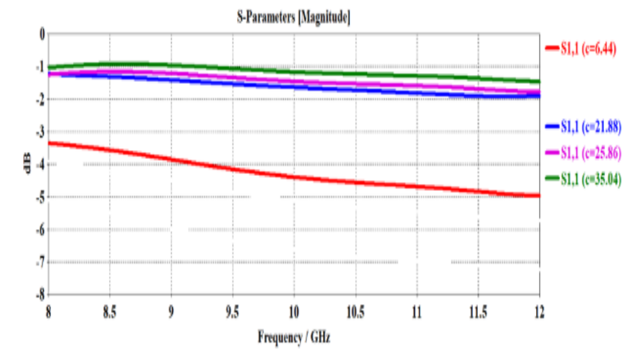


Fig. 6 – S_{11} parameter of thin film of CPBC shields

It can be noted that as conductivity increases (SB1 to SB4), S_{11} (reflection) and SE due to it i.e. SE(R) increases, S_{21} (transmittance) decreases which means absorption and SE due to it i.e. SE(A) increases.

Table 4 – S-parameters and se of CPBC EMI shields

CPBC shield	S_{11} (dB)	S_{21} (dB)	SE(R) (dB)	SE(A) (dB)	SE(T) (dB)
SB1	– 4.4	– 9.2	0.61	17.79	18.4
SB2	– 1.7	– 17.2	2.65	32.15	34.8
SB3	– 1.5	– 18.5	3.02	33.98	37.0
SB4	– 1.2	– 21.0	3.72	38.28	42.0

The highest conductivity of 35.04 S/m and SE of 40 dB at 10 GHz in X-band were obtained from the experimental study of 1 mm thick SB4 shield. The total shielding effectiveness SE_T of the various types of Conductive Polymer Bio Composites made from Sugarcane bagasse, was obtained experimentally and by simulations. The results are compared and shown in Table 5.

Table 5 – Comparison between simulation and experimental results

CPBC shield	Conductivity σ (S/m)	Shielding Effectiveness SE_T(dB)	
		Experimental	Simulation
SB1	6.44	15	18.4
SB2	21.88	30	34.8
SB3	25.86	32	37.0
SB4	35.04	40	42.0

5. CONCLUSION

The total shielding effectiveness SE_T of the Conductive Polymer Bio Composites made from Sugarcane bagasse with different compositions (SB1 to SB4) was obtained experimentally and by simulations. The results are compared at the frequency of 10 GHz, from which concluded that Increment of 1g of MWCNT alone in total wt. composition, increases SE_T by 10 dB, increment of 1.5 g of bio char alone in total wt. composition, increases SE_T by 2 dB only whereas combined increment of both bio char and MWCNT increases SE_T by 15 dB. Combined increment of 1.5g of bio char and 2g of MWCNT enhances the total shielding effectiveness (SE_T) by 25 dB. As % wt. ratio of fillers (bio char and MWCNT) increases, the conductivity and SE_T of CPBC shields increases. The SB4 shield has the highest conductivity (35.04 S/m) and highest shielding effectiveness (40 dB). The SE_T (Simulated) is more than SE_T (Experimental), because of some practical limitations of instruments, experimental setup and non-ideal environment for the measurements. The lowest % error in SE_T is 4.76 % for SB4 shield.

The major component of shielding effectiveness is absorption (SE_A). There are very limited works on the EMI shielding properties of bio char obtained from biomass. Zachariah S.M et al. [13] and C. R. Mahesha et al. [14] have reported 12.3 dB of SE for X band using PANI/PVA and bagasse fibre. Gökçen Akgül et al. [15] and Patrizia Savi et al. [16] tried commercial bio char with PMMA and cement with different fillers in X band and obtained only 10 dB of SE for thickness of 0.5 – 1 mm. Giuseppe Ruscica et al. [17] made cement paste mixed with PVC and bio charcoal and succeeded to get SE of 16 dB at 8 GHz for 4 mm thickness. Above discussed results show that the authors have obtained acceptable results of SE for SB based shields in this work.

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Виготовлення біополімерних нанокомпозитних екранів електромагнітних перешкод на основі багаси з цукрової тростини та PVA/PANI/MWCNT, а також оцінка ефективності екранування залежно від різного складу

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У цьому дослідженні виготовлено та порівняно тонкі екрани з провідного полімерного біокомпозиту, що складаються з полівінілового спирту (ПВС), поліанілінопровідного полімеру (ПАПП), багатостінних вуглецевих нанотрубок (БВНТ) та біовуглецю з цукрової тростини (БТ). Для отримання біовуглю використовується метод піролізу. Для розробки кількох видів біокомпозитних екранів біовугілля ПАПП, БВНТ та БТ змішували з ПВС за допомогою магнітної мішалки. Склади ПВС та ПАПП вагою 10 г та 2 г були фіксовані відповідно. Чотири зразки екранів (БТ1, БТ2, БТ3 та БТ4) були виготовлені шляхом зміни складу БВНТ та БТ. Використовуючи підхід Ван дер Пау, провідність екранів була оцінена на рівні 6,44, 21,88, 25,86 та 35,04 См/м відповідно. Ефективність екранування (SE) та S-параметри були розраховані за допомогою методу випробувального стенду для мікрохвильових випробувань у діапазоні X на частоті 10 ГГц. Для визначення SE та отримання S-параметрів було проведено моделювання в студійному симуляторі мікрохвильової печі CST. Зразок екрана SB4 мав максимальну SE 40 дБ (експериментально) та 42 дБ (модельовано) при товщині 1 мм, після чого показано порівняння та пояснення експериментальних та модельованих даних. Комбінація наповнювачів ПАПП та БВНТ є новим вибором, який збільшив SE біовугілля БТ. Це пояснюється вищою провідністю та кращим співвідношенням сторін біовугілля з багаси цукрової тростини, що сприяє формуванню провідної мережі на поверхні екрана. Таким чином, запропонована нова комбінація матеріалів забезпечує високу SE для дуже тонкої плівки. Використання великої кількості відходів багаси цукрової тростини для виготовлення екрану від електромагнітних перешкод не тільки зменшує електромагнітне забруднення, але й сприяє пом'якшенню забруднення навколишнього середовища.

Ключові слова: Біовугілля, Біополімерні нанокомпозити, Електромагнітні перешкоди, Ефективність екранування, S-параметри.