SUSTAINABLE ELECTROMAGNETIC INTERFERENCE SHIELDING USING WASTE-DERIVED CARBON COMPOSITES: A COMPARATIVE THEORETICAL STUDY OF SPENT COFFEE GROUNDS, ORANGE PEEL, AND RICE HUSK

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Abstract - The rapid growth of wireless communication systems, wearable electronics, smart infrastructure, and aerospace technologies has intensified the demand for efficient electromagnetic interference (EMI) shielding materials. Traditional metallic shielding materials provide excellent electromagnetic protection but suffer from disadvantages including high density, corrosion, poor flexibility, and significant environmental impact. This study proposes a sustainable alternative through the use of waste-derived carbon composites fabricated from spent coffee grounds, orange peel waste, and rice husk. A theoretical frequency-dependent model was developed to evaluate shielding effectiveness (SE) over the microwave range of 1–18 GHz, covering major practical frequency bands used in Wi-Fi, 5G, radar, and satellite communication systems. Reflection and absorption losses were calculated using classical shielding theory based on material conductivity, thickness, and electromagnetic properties. Results indicate that coffee-waste-derived carbon exhibits the highest shielding effectiveness, increasing from 33 dB to 60 dB across the investigated frequency range, followed by rice husk, 28–45 dB and orange peel 24–35 dB. The findings demonstrate the strong potential of agricultural waste valorization for lightweight, sustainable, and high-performance EMI shielding applications.

Keywords - Electromagnetic Shielding, Waste Valorization, Sustainable Materials, Green Electronics, Excel.

I. INTRODUCTION

The rapid advancement of wireless communication systems has led to substantial increase in electromagnetic radiation with modern environments[1]. Technologies operating in the microwave frequency ranges, including Wi-Fi, Bluetooth, 5G networks, radar systems, satellites, and autonomous transportation technologies, continuously emit electromagnetic radiation that may negatively influence nearby electronic equipment. This unwanted interaction, commonly known as electromagnetic interference (EMI), can result in signal distortion, reduced operational efficiency, and in severe cases, malfunction of sensitive electronic devices[2, 3].To minimize these effects, EMI shielding materials are widely used in applications such asconsumer electronics, wearable devices, smart buildings and infrastructure, electric vehicles, and biomedical instruments. Traditionally, metalssuch as aluminum, copper, and nickel have been employed because of their high electrical conductivity and excellent shielding capability. However, despite their effectiveness, these materials present several limitations, including high density, susceptibility to corrosion, limited flexibility, challenging recyclability, and environmental burden during extraction and processing[4].

Growing global emphasis on sustainable engineering has encouraged the development of environmentally friendly alternatives for EMI shielding. Among these, biomass-derived materials have gained considerable attention due to their renewable nature, low cost, biodegradability, and ability to be transformed into conductive carbon structures through thermal conversion processes such as pyrolysis[5,6].

Agriculture and food wastes are particularly attractive because they simultaneously address waste management while generating value added engineering materials. Among available biomass sources, spent coffee grounds, orange peel, and rice husk stand out as promising candidates.Spent coffee grounds contain high lignin and carbon content, making them suitable precursors for graphitic biochar after carbonization[7].Orange peel contains high concentrations of cellulose, hemicellulose, and pectin, which can yield lightweight porous carbon structures with favorable surface characteristics[8].Rice husk is unique because it naturally contains both silica and carbon, enabling enhanced dielectric polarization and improved microwave attenuation behavior[9].

This study focuses on the microwave frequency range of 1–18 GHz, selected because it covers the most relevant frequencies used in present day communication and sensing technologies. The objective is to theoretically evaluate and compare the EMI shielding performance of these three sustainable waste-derived carbon materials under identical theoretical modeling assumptions.

II. THEORETICAL BACKGROUND

Electromagnetic shielding reduces incident electromagnetic radiation through three mechanisms:reflection loss (R), absorption loss (A).

The total shielding effectiveness is:

$$SE_{Total} = R + A$$

Some studies in the literature suggest a portion of the reflection coefficient comprises the coefficient of multiple reflections M within the shielding material. When an electromagnetic wave reaches the interface between free space and a shielding material, part of the wave is reflected while the remaining portion enters the material. Inside the shield, repeated reflections occur at internal boundaries, causing further attenuation of the wave. For simplicity, many theoretical models consider these multiple internal reflections as part of the total reflection loss[10,11].

2.1. Reflection loss

Reflection loss is given by:

$$R = 39.5 + 10\log\left(\frac{\sigma}{2\pi f\mu}\right)$$

where:

- σ = electrical conductivity (S/m)
- f = frequency (Hz)
- μ = permeability (H/m)

Since the selected materials are non-magnetic:

$$\mu = \mu_0 = 4\pi \times 10^{-7}\ H/m$$

2.2. Absorption loss

Absorption loss is expressed as:

$$A = 8.686\frac{t}{\delta}$$

where:

- t = material thickness (m)
- δ = skin depth

2.3. Skin depth

Skin depth is:

$$\delta = \sqrt{\frac{1}{\pi f\mu\sigma}}$$

As frequency increases, skin depth decreases, leading to greater absorption and therefore higher shielding effectiveness.

III. MATERIALS SELECTION AND PARAMETERS USED

Three waste-derived carbon materials were selected based on availability, sustainability, and reported carbonization potential.

3.1. Spent Coffee Grounds

Spent coffee grounds are generated globally in large quantities as food waste. Due to their relatively high fixed carbon and lignin content, they can be converted into conductive porous biochar with promising electrical properties after thermal treatment[12].

3.2. Orange Peel Waste

Orange peel is an abundant agricultural food residue rich in polysaccharides such as cellulose and pectin. After carbonization, it can produce lightweight porous carbon structures suitable for microwave attenuation applications[13].

3.3. Rice Husk

Rice husk is an agricultural by-product notable for its combined carbon–silica composition. This dual-phase structure contributes not only to conductivity but also to dielectric polarization, which can improve absorption-dominated shielding[14].

To ensure fair comparison, all materials are evaluated under identical theoretical conditions, including constant thickness of 2 mm, uniform material geometry, and frequency range from1 to 18 GHz.

Parameter	Coffee	Orange	Rice Husk
conductivity σ (S/m)	120	45	70
dielectric constant ε_r	18	10	14
permeability μ_r	1	1	1
thickness (mm)	2	2	2
density (g/cm³)	0.78	0.63	0.72

Table 1: Parameters of the different materials

The conductivity values were selected from literature-reported ranges for carbonized biomass composites[15].

IV. RESULTS

The shielding effectiveness was plotted vs frequency for all three materials.

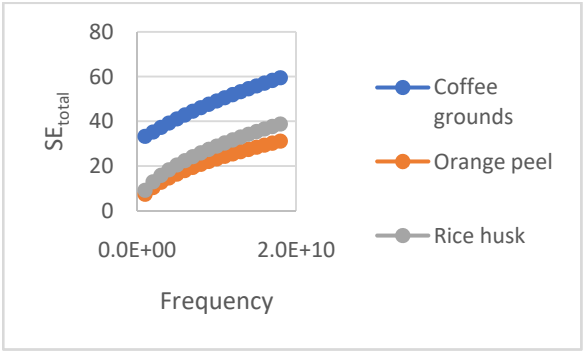


Fig 1: Shielding effectiveness vs frequency

The calculated shielding effectiveness values are summarized in the table 1 below:

Material	Low frequency SE (dB)	High frequency SE (dB)
Coffee waste	33	60
Orange peel	24	35
Rice husk	28	45

Table 1: SE in dB for coffee waste, orange peel, and rice husk at low frequency and at high frequency

V. DISCUSSION

The results show that shielding effectiveness increases with frequency for all materials. This agrees with classical shielding theory, where increasing frequency reduces skin depth and enhances absorption.

Spent coffee grounds exhibited the highest performance, increasing from 33 dB to 60 dB.This superior performance is attributed to high carbon yield after pyrolysis, improved graphitic conductivity, and interconnected porous conductive pathways. A shielding effectiveness of 60 dB corresponds to extremely high EMI attenuation, suitable for demanding aerospace and advanced electronics applications[16].

As for rice husk, it showed intermediate performance, 28-45 dB.Its strong behavior is attributed tocombined silica and carbon phases,interfacial polarization, and enhanced dielectric loss. This makes rice husk particularly effective as an absorption-dominated shielding material.Orange peel demonstrated the lowest but still useful performance, 24–35 dB.This is due tolower conductivity, reduced carbonization yield, and weaker conductive pathways. However, values above 20 dB remain sufficient for many commercial electronics and smart packaging applications[17] and these materials could be integrated intosmart building wall panels, wearable electronics,sustainable packaging, IoT enclosures, electric vehicle components, and aerospace lightweight shielding layers.

VI. CONCLUSION

A comparative theoretical study of waste-derived EMI shielding materials was performed over the technologically relevant frequency range of 1–18 GHz.Among the investigated materials, spent coffee-ground-derived carbon demonstrated the highest predicted shielding effectiveness, 33–60 dB, followed by rice husk, 28–45 dB, and orange peel 24–35 dB.The results confirm that agricultural waste can be transformed into efficient, lightweight, and sustainable EMI shielding materials, supporting circular economy principles and offering a promising route toward future green electronics.

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