UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF POLYLACTIC ACID FILLED WITH OPEFB FIBER, ACTIVATED CARBON AND MWCNTs COMPOSITES USED AS EMI SHIELDING MATERIALS

IBRAHIM ISMAILA LAKIN

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By

IBRAHIM ISMAILA LAKIN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

February 2021

DEDICATION

I hereby dedicate this thesis to the Almighty Allah who has been my help, sustainer, provider, guide, encouragement, and keeper throughout my studies and also to my parents (Late Alhaji Ibrahim Lakin and Maimuna (Kande) Pate), whose prayers and support has kept me going. Finally to my wife, brothers, and sisters who are always by my side.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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February 2021

Chairman : Associate Professor Zulkifly bin Abbas, PhD
Faculty : Science

Microwave absorbers are used in a wide range of applications to eliminate or reduce electromagnetic radiation that could interfere with a system's operation. There are several materials such as metals, various carbonaceous materials (graphene, carbon nanotubes, graphite powder and carbon fibers), conductive polymers, and their composites which are the ideal candidates for microwave absorbing applications. Conventionally metals have been used for this reason for a long time and act as the most effective microwave absorber, but they have drawback for corrosion, heavy weight and difficult processability. Industries are now concentrating on easy-to-process electrically conducting materials based on conductive polymers, conductive fillers in polymer matrix that not only have semiconductor properties but can also withstand corrosive environments, inexpensive and are light in weight. This thesis presents the development of microwave absorbers using polylactic acid (PLA) and empty fruit bunch (OPEFB) as the host. Two types of absorbers were developed in this work as an alternative for reducing the limitations of metal-based microwave absorbing materials. The first absorber utilized activated carbon (AC) fillers synthesized from OPEFB. The second type used commercial multiwalled carbon nanotubes (MWCNTs) fillers obtained from US Research Nanomaterials, Inc. OPEFB fiber was crushed and sieved to various fiber sizes using laboratory sieve test. The relationship between the different OPEFB fiber sizes and the dielectric properties was then determined.

The material composition and stuctural properties were analyzed using X-ray diffraction (XRD), field emission scanning electron microscopy (FESEM), energy dispersive X-ray analysis (EDX), and fourier transform infrared (FTIR) techniques. The relative complex permittivity of the composites was measured using open-ended coaxial probe technique while the microwave absorption properties were measured with the microstrip. The results showed that relative complex permittivity of the OPEFB fiber increased with reduced fiber size. Additionally, relative complex permittivity of the OPEFB-PLA, OPEFB-PLA-AC, and OPEFB-PLA-MWCNTs increased with filler content and were higher in the OPEFB-PLA-MWCNTs composites. At 10 GHz the dielectric constants of OPEFB-PLA, OPEFB-PLA-AC, and OPEFB-PLA-MWCNTs composites were found to be between 2.98 to 3.40, 3.14 to 3.96 and 3.40 to 4.25 respectively while the loss factor values were from 0.34 to 0.48, 0.41 to 0.52 and 0.51 to 0.64. The measured $|S_{11}|$ and $|S_{21}|$ were used to determine the reflection loss (SE_R), absorption loss (SE_A), and total electromagnetic interference (EMI) shielding effectiveness (SE_T) of all the composites. The SE_T values were found to increase with filler loadings and were higher in the OPEFB-PLA-MWCNTs composites than the OPEFB-PLA and OPEFB-PLA-AC composites which is ascribed to the MWCNTs' high loss factor. At 12 GHz, the range of SE_T values for OPEFB-PLA-MWCNTs composites was from 20.31 to 25.01 dB while OPEFB-PLA-AC and OPEFB-PLA composites were from 17.45 to 22.25 dB and 10.67 to 12.50 dB respectively, which suggest their usefulness for microwave absorption. AC derived from OPEFB fiber has the potential for use as a filler in polymeric composites and its application can reduce the cost of MWCNTs-based microwave absorbing materials significantly.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN ASID POLIKLAKTIK DIISI DENGAN SERAT OPEFB, KARBON AKTIF DAN KOMPOSIT MWCNTS DIGUNAKAN SEBAGAI BAHAN PENGHANTARAN EMI

Oleh

IBRAHIN ISMAILA LAKIN

Februari 2021

Pengerusi : Profesor Madya Zulkifly bin Abbas, PhD
Fakulti : Sains

Penyerap mikrogelombang digunakan dalam pelbagai kegunaan untuk menghilangkan atau mengurangkan sinaran elektromagnet yang boleh mengganggu operasi sistem. Terdapat beberapa bahan seperti logam, pelbagai bahan berkarbonat (graphene, nanotiub karbon, serbuk grafit dan gentian karbon), polimer berkonduksian, dan kompositnya yang sangat sesuai untuk kegunaan penyerap mikrogelombang. Secara konvensionalnya, logam telah lama digunakan untuk tujuan tersebut dan ia bertindak sebagai penyerap mikrogelombang yang paling berkesan, tetapi ia sukar untuk diproses, berat dan boleh menyebabkan hakisan. Kini, industri tertumpu kepada bahan pengalir elektrik yang mudah diproses berasaskan polimer berkonduksian, pengisi berkonduksian dalam matriks polimer bukan sahaja bersifat semikonduktor tetapi juga murah, ringan dan dapat menahan persekitaran yang mengkakis. Kajian ini membentangkan perkembangan penyerap mikrogelombang menggunakan asid polilaktik (PLA) dan tandan kosong (OPEFB) sebagai perumah. Dua jenis penyerap dibangunkan dalam kajian ini sebagai alternatif dalam mengurangkan kekurangan bahan penyerap mikrogelombang berasaskan logam. Penyerap pertama menggunakan pengisi karbon aktif (AC) yang disintesis daripada OPEFB. Jenis kedua menggunakan pengisi nanotiub karbon berbilang dinding komersial (MWCNTs) yang diperoleh dari US Research Nanomaterials, Inc. Serat OPEFB banyak dijumpai sebagai sisa pepejal dari kilang kelapa sawit. Serat OPEFB dihancurkan dan diayak kepada pelbagai saiz serat menggunakan ujian saringan makmal. Hubungan antara pelbagai saiz serat OPEFB dan pemalar dielektrik ditentukan.

Komposisi bahan dan sifat struktur dianalisis dengan menggunakan belauan sinar-X (XRD), pemancaran medan mikroskopi imbasan elektron (FESEM), analisis tenaga serakan sinaran-X (EDX), dan teknik transformasi Fourier inframerah (FTIR). Kebertelusan komposit relatif rumit diukur menggunakan teknik kuar sepaksi terbuka sementara itu, sifat serapan mikrogelombang diukur menggunakan mikrojalur. Dapatan

menunjukkan kebertelusan komposit relatif rumit serat OPEFB meningkat dengan saiz serat yang dikurangkan. Selain itu, kebertelusan komposit relatif rumit bagi OPEFB-PLA, OPEFB-PLA-AC, dan OPEFB-PLA-MWCNT meningkat dengan kandung pengisi dan lebih tinggi di dalam komposit OPEFB-PLA-MWCNT. Pada 10 GHz, pemalar dielektrik OPEFB-PLA, OPEFB-PLA-AC, dan komposit OPEFB-PLA-MWCNT masing-masing didapati berada di antara 2.98 hingga 3.40, 3.14 hingga 3.96 dan 3.40 hingga 4.25. Sementara itu, nilai faktor kerugian adalah dari 0.34 hingga 0.48, 0.41 hingga 0.52 dan 0.51 hingga 0.64. Ukuran $|S_{11}|$ and $|S_{21}|$ digunakan untuk menentukan kehilangan pantulan (SE_R), kehilangan serapan (SE_A), dan jumlah gangguan elektromagnet (EMI) keberkesanan pemerisaian (SE_T) bagi semua komposit. Nilai SE_T didapati meningkat dengan muatan pengisi dan lebih tinggi pada komposit OPEFB-PLA-MWCNTs berbanding komposit OPEFB-PLA dan OPEFB-PLA-AC yang dikaitkan dengan faktor kehilangan tinggi MWCNT. Pada 12 GHz, julat nilai SE_T bagi komposit OPEFB-PLA-MWCNT adalah dari 20.31 hingga 25.01 dB sementara komposit OPEFB-PLA-AC dan OPEFB-PLA masing-masing dari 17.45 hingga 22.25 dB dan 10.67 hingga 12.50 dB. Ini membuktikan kebergunaanya dalam serapan mikrogelombang. AC, terbitan dari gentian OPEFB berpotensi untuk digunakan sebagai pengisi dalam komposit polimer dan kegunaannya dapat mengurangkan kos bahan penyerap gelombang mikro berasaskan MWCNT dengan ketara.

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Zulkifly bin Abbas, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Chairman)

Nor Azowa binti Ibrahim, PhD
Associate Professor
Faculty of Science
Universiti Putra Malaysia
(Member)

Mohd Amiruddin bin Abd Rahman, PhD
Senior Lecturer
Faculty of Science
Universiti Putra Malaysia
(Member)

ZALILAH MOHD SHARIFF, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 12 August 2021

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LIST OF ABBREVIATIONS AND SYMBOLS

ω	Angular frequency
η_0	Impedance in free space
∇	Laplacian vector
γ	Propagation constant
ρ_q	The electric charge density
ε_r	The relative dielectric of the substrate
ABC	Absorbing boundary condition
AC	Activated carbon
B	The magnetic flux density
BET	Brunauer Emmett, and Teller
CEM	Computational electromagnetic
d	Sample thickness
D	The electric displacement
dB	Decibels
EDX	Energy-dispersive X-ray
EM	Electromagnetic
EMI	Electromagnetic interference shielding
E_z	Longitudinal electric field
f	Frequency
FDTD	Finite difference time domain
FEM	Finite Element Method
FESEM	Field electron scanning electron microscopy

FTIR	Fourier transforms infrared
H_z	Longitudinal magnetic field
J	The current density
k_0	Free-space wave number
MoM	Method of Moment
MUT	Materials under test,
MWCNTs	Multiwalled carbon nanotubes
OECP	Open Ended Coaxial Probe
OPEFB	Oil palm empty fruit bunch
P_1	Power measured with the material inserted
P_2	Power measured without material inserted
PANI	Polyaniline
PCL	Polycaprolactone
PEK	Poly (Ether Ketone)
PLA	Polylactic acids
PML	Perfectly match layer
PNA	Professional network analyzer
PVP	Polyvinypyrrolidone
RAM	Radar absorbing material
RBC	Reflectionless boundary condition
RF	Radiofrequency
RWG	Rectangular waveguide
S_{11}	Input reflection coefficient of port one
S_{21}	Transmission coefficient port two
SE	Shielding effectiveness

SE_A	Absorption shielding effectiveness
SE_R	Reflection shielding effectiveness
SE_T	Shielding effectiveness
T/R	Reflection/Transmission
TE	Transverse Electric
TEM	Transverse electromagnetic modes
TM	Transverse Magnetic
XRD	X-ray diffraction
Z_{in}	Impedance of the absorbing material
Z_O	Impedance of free space
β	Phase constant
ε'	Dielectric constant
ε''	Loss factor
ε^*	Complex permittivity
μ	Permeability
σ	Electrical conductivity
ε	Permittivity

CHAPTER 1

INTRODUCTION

The need for microwave absorbers and radar-absorbing materials are on the rise in military application dealing with reduction of radar signature air crafts and ships whilst in civilian applications dealing with electromagnetic interference among electronic and telecommunication systems. Composite absorber that uses carbon based materials in conjunction with a polymer matrix produces flexibility which can be manipulated by changes (in formulations) in both the filler and the matrix. Depending on the application for which the absorber is intended, the percentage of filler and the matrix are two important factors to be understood. In addition, microwave absorption properties are determined by the complex permittivity and permeability, sample thickness, microstructure of the absorber, and class of material. In the industry of aerospace, for example, innovative solutions are needed to shield effectively sensitive electronic equipment such as antennas from EMI without adding much of weight to aircraft. In the past, the problem of EMI was tackled by isolating the electronic device through some metallic housing. Metals are excellent conductors of electricity that are capable to absorb, reflect, and transmit electromagnetic interference. Metals like Silver, Iron, Aluminum, Nickel Copper, and Barium were used in most of the EMI shielding applications (Xiang et al., 2007). The disadvantage was that the metals were easily susceptible to oxidation or corrosion and so could not be utilized for outside applications. The heavyweight and price of the metal shields also limit the use of metals as shielding materials (Jagatheesan et al., 2015). Nowadays, the most common method of shielding by reflection is the use of metallic plates or absorption by carbon-based materials. Polymeric materials have also acquired popularity due to their flexibility, lightweight, corrosion resistance, and lower cost to metals. Researches had also been carried out on the applications of polymer composites incorporated with conductive fillers, fibers, nanotubes, and dispersing particles (Chen et al., 2015). The metal plate problems centered primarily on the discomfort of poor mechanical flexibility due to high rigidity, high weight density and high cost. Low density, high conductivity, efficient broadband absorption, and excellent thermal stability are the main parameters for a typical EM absorbing material. The microwave absorption mechanism classifies the materials into two main sections; dielectric loss materials and materials that are magnetically lossy. (Arief et al., 2017). The design of an EMI shielding material with a certain degree of attenuation while meeting a set of environmental requirements, retaining economics and regulating shielding have been suggested. The main purpose behind the proper design of the shield is to create a product that can comply with International electromagnetic Interference Regulatory Standards. The research of new active materials used as microwave absorbers for the EMI shielding of various electronic devices is one of present-day activities (Paligova et al., 2004).

Measurement of complex permittivity is required not only for scientific but also for industrial applications. Dielectric properties measurement is an important factor in defining the physical and chemical properties related to storage and energy loss in various kind of materials (Wee et al., 2009). The term dielectric constant is misleading, the dependency on dielectric material frequency causes it to have two parts, that is, the real and imaginary permittivity. The ratio of the imaginary part to the real part of permittivity is referred to as loss tangent. Permittivity and permeability are complex numbers of which the imaginary part is correlated with losses.

Scattering parameter, permittivity and permeability of materials measured using microwaves components are controlled by the basic properties of microwaves. In good conducting materials, microwave has low penetrating depth. To investigate the interaction between microwaves materials, Maxwell’s equation is often employed. Properties like propagation mode, reflection, refraction, transmission, and impedance are defined from the equation. The broad nature of material properties allows the use of different techniques for measurement at microwave frequency range. A number of methods have been used in the measurements of electromagnetic properties at microwave frequencies. Amongst these methods are the transmission and reflection line technique, free space measurement technique, open-ended coaxial probe technique, and resonant method (Teppati et al., 2013).

1.1 Problem Statement

The incorporation of OPEFB fiber into PLA matrix is expected to improve the complex permittivity, absorption, and attenuation as well as reduce the fabricated composites transmission coefficient making a better microwave absorbing material. OPEFB-PLA composites have been used extensively in many microwave application. However, due to lack of detailed knowledge on the relationship between the filler composition and the electromagnetic properties, its potential has not been fully exploited. The dielectric properties and scattering parameters of OPEFB-PLA composites of different filler and types, matrix and material properties have not been studied in depth both theoretically and experimentally (Abdalhadi et al., 2018). In developing absorbing composites, ferrites are commonly used. However, like any other metals ferrites are heavy, corrosive, expensive, and non-biodegradable. Therefore, the use of metals such as ferrites for EMI shielding could lead to galvanic corrosion which in turn increased the nonlinearity behavior and decreased its shielding effectiveness.

Oil palm empty fruit bunch fiber (OPEFB) offers various advantages such as low cost, low density, better thermal and insulating properties, good flexural strength, and biodegradability. Although microwave properties of OPEFB-PLA/PCL reinforced with Fe_2O_3 have recently been studied (Abdalhadi et al., 2018; Mensah et al., 2019) but the dielectric loss factor for the nanocomposites was found to be low and microwave absorbers need to have high loss factor for higher absorbing properties. In this research AC was synthesized from OPEFB and the dielectric properties subsequently improved after activating the OPEFB fiber via physical activation. The AC with improved dielectric properties could be useful in reducing the limitations of the frequently used fibers for microwave absorption applications. Recently, the addition of multiwalled carbon nanotubes (MWCNTs) into metal, ceramic, or polymer matrix has been carefully studied and a wide variety of different characteristics have been found (Kim et al., 2018 and Mondal et al., 2018). The incorporation of AC and MWCNTs fillers into OPEFB-

PLA composites could enhanced the permittivity and microwave absorbing properties of OPEFB-PLA-AC and OPEFB-PLA-MWCNTs composites.

The conventional method to determine the complex permittivity of the composites materials is to place the sample in a closed waveguide. The approach is difficult as the sample must be firmly placed into the waveguide avoiding any air gaps. In this work, the open-ended coaxial probe (OEC) technique was used to investigate the complex permittivity of OPEFB-PLA, OPEFB-PLA-MWCNTs, and OPEFB-PLA-AC composites. The microwave attenuation due to sample does not only depend on the complex permittivity but also the sample thickness. Thick samples measurements are always problematic when using waveguide technique due air gap problems. In this research, the attenuation of the samples was also analyzed using the open line transmission (microstrip) technique. Visualization of the electromagnetic field in the samples was carried out where the samples were discretize into small meshes using the Finite Element Method (FEM)

1.2 Research Objectives

The main objectives of this research are as follows;

1. To characterize the structure, microstructure and elemental properties of OPEFB-PLA, OPEFB-PLA-MWCNTs composites using XRD, FTIR, FESEM, and EDX techniques.

2. To determine the effect of OPEFB fiber size on its dielectric constant and loss factor values

3. To determine the complex permittivity and scattering parameters of OPEFB-PLA, OPEFB-PLA-AC, and OPEFB-PLA-MWCNTs composites using the open-ended coaxial probe and microstrip line technique respectively. Also to calculate the Scattering parameter values of the composites using FEM and compare the results with microstrip line technique then visualize the electromagnetic field distribution of the composites using FEM for various filler percentage.

4. To calculate the reflection loss, absorption loss, and total EMI shielding effectiveness of OPEFB-PLA, OPEFB-PLA-AC, and OPEFB-PLA-MWCNTs composites.

1.3 The Scope of the study

In this study, the melt blending technique using a Brabender machine to fabricate OPEFB-PLA biocomposites with MWCNTs and AC incorporated into the composites to enhance their electrical properties. The effect of the different percentages of MWCNTs and AC filler concentrations on the dielectric properties would be investigated using the open-ended coaxial probe technique. The use of a microstrip transmission line would be made to investigate the effect of MWCNTs and AC filler on the scattering parameters of OPEFB-PLA-AC and, OPEFB-PLA-MWCNTs composites. FEM COMSOL software would also be used to calculate the scattering parameters and for simulation of electromagnetic waves excited through OPEFB-PLA, OPEFB-PLA-AC, and OPEFB-PLA-MWCNTs composites samples when placed on the microstrip transmission line. The results obtained through measurement and simulation would also be compared. The microstructure, elemental and bonding types would be characterized using equipment such as XRD, FESEM, EDX, and FTIR.

1.4 Organization of the Thesis

This thesis consist of six chapters and appendix. Chapter one gives the general introduction on EMI and the materials used for this research. Followed by the statement of the problem, objectives of the study, the scope of the study and the thesis layout.

Chapter two presents the reviews on the properties of OPEFB fiber, PLA, AC, and MWCNTs. Composite material synthesis methods and microwave characterization techniques are also reviewed in this chapter. Finally, the FEM as a numerical technique for the simulation of electrical field distribution and the determination of the S-parameters of samples placed on the microstrip is reviewed.

Chapter 3 presents the theory chapter and it discusses the theoretical concepts of the dielectric properties, polarization and basic electromagnetic wave equations. It concludes with the transmission and reflection coefficients calculation procedures with FEM formulation techniques. Furthermore, sample preparation, morphological, microstructural and electromagnetic characterizations are discussed in chapter 4. The use of the OEC, microstrip and FEM method are fully discussed in relation to the electromagnetic characterization using XRD, FESEM, EDX, and FTIR are all discussed in details.

Chapter 5 is presented in six sections and it discusses the results of the material characterization and simulations involving all the samples used in this research. The first section presents and discusses the results of morphological and microstructural characterizations of the OPEFB fiber, PLA, AC powder, OPEFB-PLA, OPEFB-PLA-AC, and OPEFB-PLA-MWCNTs composites using measurement technique such as XRD, FESEM, EDX, and FTIR. This is followed by the second section which presents and discusses the results of the complex permittivity of the OPEFB fiber, PLA, AC powder, and the fabricated composites using the OEC technique. The third section of the chapter presents and discusses the results of FEM simulation and visualization of electric field intensity distribution for the OPEFB-PLA, OPEFB-PLA-AC, and OPEFB-PLA-MWCNTs composites based on the microstrip. The fourth and fifth sections discusses the results of the S-parameters measurement of the OPEFB-PLA, OPEFB-PLA-AC, and OPEFB-PLA-MWCNTs composites using the microstrip technique and FEM respectively. The sixth section discusses the results of material absorption where the S-parameters S_{11} and S_{21} of the composites obtained from the microstrip technique were used to calculate the reflection shielding effectiveness (SE_R), absorption shielding effectiveness (SE_A) and the total shielding effectiveness (SE_T) of the composites.

Finally, chapter six summarizes and draws conclusions based on the findings of this research and offers suggestions for the future research in this area of study.

REFERENCES

Abbas, Z. (2000). Determination of the Dielectric Properties of the Material at Microwave Frequencies Using Rectangular Dielectric Waveguide, PhD Thesis, University of Leeds.

Abdalhadi, D. M., Abbas, Z., Ahmad, A. F., & Ibrahim, N. A. (2017). Determining the Complex Permittivity of Oil Palm Empty Fruit Bunch Fibre Material by Open-ended Coaxial Probe Technique for Microwave Applications. *BioResources*, *12*(2), 3976-3991.

Abdalhadi, D. M., Abbas, Z., Ahmad, A. F., Matori, K. A., & Esa, F. (2018). Controlling the Properties of OPEFB/PLA Polymer Composite by Using Fe 2 O 3 for Microwave Applications. *Fibers and Polymers*, *19*(7), 1513-1521.

Abdul Khalil, H. P. S., Siti Alwani, M., Ridzuan, R., Kamarudin, H., & Khairul, A. (2008). Chemical composition, morphological characteristics, and cell wall structure of Malaysian oil palm fibers. *Polymer-Plastics Technology and Engineering*, *47*(3), 273-280.

Abiola, O. S., Kupolati, W. K., Sadiku, E. R., & Ndambuki, J. M. (2014). Utilisation of natural fibre as modifier in bituminous mixes: A review. *Construction and Building Materials*, *54*, 305-312.

Afifah Mahmud, N., Osman, N., & Jani, A. M. M. (2018). Characterization of Acid Treated Activated Carbon From Oil Palm Empty Fruit Bunches (EFB). *JPhCS*, *1083*(1), 012049.

Ahmad, A. F., Ab Aziz, S., Abbas, Z., Obaiys, S. J., Khamis, A. M., Hussain, I. R., & Zaid, M. H. M. (2018). Preparation of a chemically reduced graphene oxide reinforced epoxy resin polymer as a composite for electromagnetic interference shielding and microwave-absorbing applications. *Polymers*, *10*(11), 1180.

Ahmed, M. J. (2016). Application of agricultural based activated carbons by microwave and conventional activations for basic dye adsorption. *Journal of Environmental Chemical Engineering*, *4*(1), 89-99.

Ali, N. N., Atassi, Y., Salloum, A., Charba, A., Malki, A., & Jafarian, M. (2018). Comparative study of microwave absorption characteristics of (Polyaniline/NiZn ferrite) nanocomposites with different ferrite percentages. *Materials Chemistry and Physics*, *211*, 79-87.

Ali, M. E., Yong, C. K., Ching, Y. C., Chuah, C. H., & Liou, N. S. (2015). Effect of single and double stage chemically treated kenaf fibers on mechanical properties of polyvinyl alcohol film. *BioResources*, *10*(1), 822-838.

Ao, W., Fu, J., Mao, X., Kang, Q., Ran, C., Liu, Y., ... & Dai, J. (2018). Microwave assisted preparation of activated carbon from biomass: A review. *Renewable and Sustainable Energy Reviews*, *92*, 958-979.

Arief, I., Biswas, S., & Bose, S. (2017). FeCo-anchored reduced graphene oxide framework-based soft composites containing carbon nanotubes as highly efficient microwave absorbers with excellent heat dissipation ability. *ACS applied materials & interfaces*, *9*(22), 19202-19214.

Arjmand, M., Apperley, T., Okoniewski, M., & Sundararaj, U. (2012). Comparative study of electromagnetic interference shielding properties of injection molded versus compression molded multi-walled carbon nanotube/polystyrene composites. *Carbon*, *50*(14), 5126-5134.

Arora, M., Wahab, M. A., & Saini, P. (2014). Permittivity and electromagnetic interference shielding investigations of activated charcoal loaded acrylic coating compositions. *Journal of Polymers*, *2014*.

Ayyaswamy, J. P. K., Sattanathan, S., Ramachandran, B., & Nadarajan, M. (2019). *Banana Stem Based Activated Carbon as Filler in Polymer Composites for Automobile Applications* (No. 2019-28-0093). SAE Technical Paper.

Azadeh, M., Zamani, C., Ataie, A., & Morante, J. R. (2018). Three-dimensional rice husk-originated mesoporous silicon and its electrical properties. *Materials Today Communications*, *14*, 141-150.

Bahr, A. J. (1982). *Microwave nondestructive testing methods*(Vol. 1). CRC Press.

Bakare, A. A. (2017). Numerical solution of second order differential equations by method of finite element. department of mathematics, Faculty of Physical Sciences, University of Ilorin, Ilorin.

Baker, C. O., Huang, X., Nelson, W., & Kaner, R. B. (2017). Polyaniline nanofibers: broadening applications for conducting polymers. *Chemical Society Reviews*, *46*(5), 1510-1525.

Baker-Jarvis, J., Vanzura, E. J., & Kissick, W. A. (1990). Improved technique for determining complex permittivity with the transmission/reflection method. *IEEE Transactions on microwave theory and techniques*, *38*(8), 1096-1103.

Barkanov, E. (2001). Introduction to the finite element method. *Institute of Materials and Structures Faculty of Civil Engineering Riga Technical University*, 1-70.

Belaabed, B., Lamouri, S., Naar, N., Bourson, P., & Hamady, S. O. S. (2010). Polyaniline-doped benzene sulfonic acid/epoxy resin composites: structural, morphological, thermal and dielectric behaviors. *Polymer journal*, *42*(7), 546.

Beltrame, K. K., Cazetta, A. L., de Souza, P. S., Spessato, L., Silva, T. L., & Almeida, V. C. (2018). Adsorption of caffeine on mesoporous activated carbon fibers prepared from pineapple plant leaves. *Ecotoxicology and environmental safety*, *147*, 64-71.

Bhawal, P., Das, T. K., Ganguly, S., Mondal, S., Ravindren, R., & Das, N. C. (2017). Fabrication of light weight mechanically robust short carbon fiber/ethylene methyl acrylate polymeric nanocomposite for effective electromagnetic interference shielding. *J Polym Sci Appl*, *1*, 2.

Bibi, M., Abbas, S. M., Ahmad, N., Muhammad, B., Iqbal, Z., Rana, U. A., & Khan, S. U. D. (2017). Microwaves absorbing characteristics of metal ferrite/multiwall carbon nanotubes nanocomposites in X-band. *Composites Part B: Engineering*, *114*, 139-148.

Bikky, R., Badi, N., & Bensaoula, A. (2010). Effective Medium Theory of Nanodielectrics for Embedded Energy Storage Capacitors. In *COMSOL Conference*.

Botlhoko, O. J., Ramontja, J., & Ray, S. S. (2017). Thermal, mechanical, and rheological properties of graphite-and graphene oxide-filled biodegradable polylactide/poly (ε-caprolactone) blend composites. *Journal of Applied Polymer Science*, *134*(40), 45373.

Cazacu, G., Darie-Nita, R. N., Chirila, O., Totolin, M., Asandulesa, M., Ciolacu, D. E., ... & Vasile, C. (2017). Environmentally friendly polylactic acid/modified lignosulfonate biocomposites. *Journal of Polymers and the Environment*, *25*(3), 884-902.

Challabi, A. J. H., Chieng, B. W., Ibrahim, N. A., Ariffin, H., & Zainuddin, N. (2019). Effect of Superheated Steam Treatment on the Mechanical Properties and Dimensional Stability of PALF/PLA Biocomposite. *Polymers*, *11*(3), 482.

Chandra, R. J., Shivamurthy, B., Kulkarni, S. D., & Kumar, M. S. (2019). Hybrid polymer composites for EMI shielding application-a review. *Materials Research Express*, *6*(8), 082008.

Chang, T., Li, Z., Yun, G., Jia, Y., & Yang, H. (2013). Enhanced photocatalytic activity of ZnO/CuO nanocomposites synthesized by hydrothermal method. *Nano-Micro Letters*, *5*(3), 163-168.

Chauhan, S. S., Verma, P., Malik, R. S., & Choudhary, V. (2018). Thermomechanically stable dielectric composites based on poly (ether ketone) and BaTiO3 with improved electromagnetic shielding properties in X-band. *Journal of Applied Polymer Science*, *135*(26), 46413.

Chayid, M. A., & Ahmed, M. J. (2015). Amoxicillin adsorption on microwave prepared activated carbon from Arundo donax Linn: isotherms, kinetics, and thermodynamics studies. *Journal of Environmental Chemical Engineering*, *3*(3), 1592-1601.

Chen, X., Liu, L., Liu, J., & Pan, F. (2015). Microstructure, electromagnetic shielding effectiveness and mechanical properties of Mg–Zn–Y–Zr alloys. *Materials & Design (1980-2015)*, *65*, 360-369.

Ching, Y. C., & Ng, T. S. (2014). Effect of preparation conditions on cellulose from oil palm empty fruit bunch fiber. *BioResources*, *9*(4), 6373-6385.

Chowdhury, Z. Z., Abd Hamid, S. B., Rahman, M. M., & Rafique, R. F. (2016). Catalytic activation and application of micro-spherical carbon derived from hydrothermal carbonization of lignocellulosic biomass: statistical analysis using Box–Behnken design. *RSC advances*, *6*(104), 102680-102694.

Courant, R. (1943). *Variational methods for the solution of problems of equilibrium and vibrations*. Verlag nicht ermittelbar.

da Silva, C. P., dos Santos, A. V., Oliveira, A. S., & da Guarda Souza, M. O. (2018). Synthesis of composites and study of the thermal behavior of sugarcane bagasse/iron nitrate mixtures in different proportions. *Journal of Thermal Analysis and Calorimetry*, *131*(1), 611-620.

Davidson, D. B. (2010). *Computational electromagnetics for RF and microwave engineering*. Cambridge University Press.

Davidson, D. B., & Aberle, J. T. (2004). An introduction to spectral domain method-of-moments formulations. *IEEE Antennas and propagation Magazine*, *46*(3), 11-19.

De Rosa, I. M., Dinescu, A., Sarasini, F., Sarto, M. S., & Tamburrano, A. (2010). Effect of short carbon fibers and MWCNTs on microwave absorbing properties of polyester composites containing nickel-coated carbon fibers. *Composites Science and Technology*, *70*(1), 102-109.

Dimpe, K. M., & Nomngongo, P. N. (2019). Application of activated carbon-decorated polyacrylonitrile nanofibers as an adsorbent in dispersive solid-phase extraction of fluoroquinolones from wastewater. *Journal of pharmaceutical analysis*, *9*(2), 117-126.

Dosoudil, R., Ušáková, M., Franek, J., Grusková, A., & Sláma, J. (2008). Dispersion of complex permeability and EM-wave absorbing characteristics of polymer-based composites with dual ferrite filler. *Journal of Magnetism and Magnetic Materials*, *320*(20), e849-e852.

Duan, H., Zhao, M., Yang, Y., Zhao, G., & Liu, Y. (2018). Flexible and conductive PP/EPDM/Ni coated glass fiber composite for efficient electromagnetic interference shielding. *Journal of Materials Science: Materials in Electronics*, *29*(12), 10329-10336.

DuPont Teflon, P. T. F. E. (1996). Fluoropolymer Resin Properties Handbook.

Edwards, T. C., & Steer, M. B. (2016). *Foundations for microstrip circuit design*: John Wiley & Sons.

Esa, F., Abbas, Z., Mohd Idris, F., & Hashim, M. (2015). Characterization of NixZn1−xFe2O4 and Permittivity of Solid Material of NiO, ZnO, Fe2O3, and NixZn1−xFe2O4 at Microwave Frequency Using Open Ended Coaxial Probe. *International Journal of Microwave Science and Technology*, *2015*.

Gandhi, N., Singh, K., Ohlan, A., Singh, D. P., & Dhawan, S. K. (2011). Thermal, dielectric and microwave absorption properties of polyaniline–CoFe2O4 nanocomposites. *Composites Science and Technology*, *71*(15), 1754-1760.

Gupta, A. K., Biswal, M., Mohanty, S., & Nayak, S. K. (2016). Eco-friendly lignocellulosic natural fibre reinforced recycled polymer composite with modified interface and reactive compatibilization: A micromechanical analysis with various model. *Materials Focus*, *5*(2), 106-118.

Hamid, M. Z. A., Ibrahim, N. A., Yunus, W. M. Z. W., Zaman, K., & Dahlan, M. (2010). Effect of grafting on properties of oil palm empty fruit bunch fiber reinforced polycaprolactone biocomposites. *Journal of reinforced plastics and composites*, *29*(18), 2723-2731.

Hasan, M. R., & Al Suman, A. (2012). Substrate Height and Dielectric Constant Dependent Performance of Circular Micro Strip Patch Array Antennas for Broadband Wireless Access. *J. Emerg. Trends Comput. Inf. Sci.*, *3*(10), 1392-1397.

Hassan, A., Salema, A. A., Ani, F. N., & Bakar, A. A. (2010). A review on oil palm empty fruit bunch fiber-reinforced polymer composite materials. *Polymer Composites*, *31*(12), 2079-2101.

Hazra, S., Ghosh, B. K., Patra, M. K., Jani, R. K., Vadera, S. R., & Ghosh, N. N. (2015). A novel 'one-pot'synthetic method for preparation of (Ni0. 65Zn0. 35Fe2O4) x–(BaFe12O19) 1− x nanocomposites and study of their microwave absorption and magnetic properties. *Powder technology*, *279*, 10-17.

Hidayu, A. R., Mohamad, N. F., Matali, S., & Sharifah, A. S. A. K. (2013). Characterization of activated carbon prepared from oil palm empty fruit bunch using BET and FT-IR techniques. *Procedia Engineering*, *68*, 379-384.

Huang, L., Liu, X., & Yu, R. (2018). Enhanced microwave absorption properties of rod-shaped Fe2O3/Fe3O4/MWCNTs composites. *Progress in Natural Science: Materials International*, *28*(3), 288-295.

Ibrahim Lakin, I., Abbas, Z., Azis, R. S., & Abubakar Alhaji, I. (2020). Complex Permittivity and Electromagnetic Interference Shielding Effectiveness of OPEFB Fiber-Polylactic Acid Filled with Reduced Graphene Oxide. *Materials*, *13*(20), 4602.

Ibrahim, N. A., Hashim, N., Rahman, M. A., & Yunus, W. Z. W. (2011). Mechanical properties and morphology of oil palm empty fruit bunch—polypropylene composites: effect of adding ENGAGETM 7467. *Journal of Thermoplastic Composite Materials*, *24*(5), 713-732.

Jacob, M., Varughese, K. T., & Thomas, S. (2006). Dielectric characteristics of sisal–oil palm hybrid biofibre reinforced natural rubber biocomposites. *Journal of materials science*, *41*(17), 5538-5547.

Jagatheesan, K., Ramasamy, A., Das, A., & Basu, A. (2015). Fabrics and their composites for electromagnetic shielding applications. *Textile Progress*, *47*(2), 87-161.

Jayamani, E., Hamdan, S., Rahman, M. R., & Bakri, M. K. B. (2014). Comparative study of dielectric properties of hybrid natural fiber composites. *Procedia Engineering*, *97*, 536-544.

Jia, W., Gong, R. H., & Hogg, P. J. (2014). Poly (lactic acid) fibre reinforced biodegradable composites. *Composites Part B: Engineering*, *62*, 104-112.

Jiang, D., Murugadoss, V., Wang, Y., Lin, J., Ding, T., Wang, Z., ... & Guo, Z. (2019). Electromagnetic interference shielding polymers and nanocomposites-a review. *Polymer Reviews*, *59*(2), 280-337.

Jin, J. M. (2015). *The finite element method in electromagnetics*. John Wiley & Sons.

Jung, M., Lee, Y. S., Hong, S. G., & Moon, J. (2020). Carbon nanotubes (CNTs) in ultra-high performance concrete (UHPC): Dispersion, mechanical properties, and electromagnetic interference (EMI) shielding effectiveness (SE). *Cement and Concrete Research*, *131*, 106017.

Kabir, M. M., Wang, H., Lau, K. T., & Cardona, F. (2012). Chemical treatments on plant-based natural fibre reinforced polymer composites: An overview. *Composites Part B: Engineering*, *43*(7), 2883-2892.

Kashi, S., Gupta, R. K., Baum, T., Kao, N., & Bhattacharya, S. N. (2016). Morphology, electromagnetic properties and electromagnetic interference shielding performance of poly lactide/graphene nanoplatelet nanocomposites. *Materials & Design*, *95*, 119-126.

Keiluweit, M., Nico, P. S., Johnson, M. G., & Kleber, M. (2010). Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environmental science & technology*, *44*(4), 1247-1253.

Kim, H. M., Kim, K., Lee, C. Y., Joo, J., Cho, S. J., Yoon, H. S., ... & Epstein, A. J. (2018). Electrical conductivity and electromagnetic interference shielding of multiwalled carbon nanotube composites containing Fe catalyst. *Applied Physics Letters*, *84*(4), 589-591.

Kochetov, R., Andritsch, T., Morshuis, P. H., & Smit, J. J. (2012). Anomalous behaviour of the dielectric spectroscopy response of nanocomposites. *IEEE Transactions on Dielectrics and Electrical Insulation*, *19*(1), 107-117.

Kristiani, A., Effendi, N., Aristiawan, Y., Aulia, F., & Sudiyani, Y. (2015). Effect of combining chemical and irradiation pretreatment process to characteristic of oil palm's empty fruit bunches as raw material for second generation bioethanol. *Energy Procedia*, *68*, 195-204.

Kumar, K. P., & Sekaran, A. S. J. (2014). Some natural fibers used in polymer composites and their extraction processes: A review. *Journal of Reinforced Plastics and Composites*, *33*(20), 1879-1892.

Liou, T. H., & Wu, S. J. (2009). Characteristics of microporous/mesoporous carbons prepared from rice husk under base-and acid-treated conditions. *Journal of hazardous materials*, *171*(1-3), 693-703.

Majidifar, S., & Karimi, G. (2016). New approach for dielectric constant detection using a microstrip sensor. *Measurement*, *93*, 310-314.

Mandal, S. K., Singh, S., Dey, P., Roy, J. N., Mandal, P. R., & Nath, T. K. (2016). Frequency and temperature dependence of dielectric and electrical properties of TFe2O4 (T= Ni, Zn, Zn0. 5Ni0. 5) ferrite nanocrystals. *Journal of Alloys and Compounds*, *656*, 887-896.

Meli, A. D., Abbas, Z., Zaid, M. H. M., & Ibrahim, N. A. (2019). The Effects of SLS on Structural and Complex Permittivity of SLS-HDPE Composites. *Advances in Polymer Technology*, *2019*.

Menéndez, J. A., Arenillas, A., Fidalgo, B., Fernández, Y., Zubizarreta, L., Calvo, E. G., & Bermúdez, J. M. (2010). Microwave heating processes involving carbon materials. *Fuel Processing Technology*, *91*(1), 1-8.

Mensah, E. E., Abbas, Z., Azis, R. A. S., & Khamis, A. M. (2019). Enhancement of Complex Permittivity and Attenuation Properties of Recycled Hematite (α-Fe2O3) Using Nanoparticles Prepared via Ball Milling Technique. *Materials*, *12*(10), 1696.

Mensah, E. E., Abbas, Z., Azis, R. A. S., Ibrahim, N. A., & Khamis, A. M. (2019). Complex Permittivity and Microwave Absorption Properties of OPEFB Fiber–Polycaprolactone Composites Filled with Recycled Hematite (α-Fe2O3) Nanoparticles. *Polymers*, *11*(5), 918.

Mesfin, H. M., Hermans, S., Huynen, I., Delcorte, A., & Bailly, C. (2016). Thin oriented polymer carbon nanotube composites for microwave absorption. *Materials Today: Proceedings*, *3*(2), 491-496.

Mondal, S., Ganguly, S., Rahaman, M., Aldalbahi, A., Chaki, T. K., Khastgir, D., & Das, N. C. (2016). A strategy to achieve enhanced electromagnetic interference shielding at low concentration with a new generation of conductive carbon black in a chlorinated polyethylene elastomeric matrix. *Physical Chemistry Chemical Physics*, *18*(35), 24591-24599.

Mondal, S., Das, P., Ganguly, S., Ravindren, R., Remanan, S., Bhawal, P., ... & Das, N. C. (2018). Thermal-air ageing treatment on mechanical, electrical, and electromagnetic interference shielding properties of lightweight carbon nanotube based polymer nanocomposites. *Composites Part A: Applied Science and Manufacturing*, *107*, 447-460.

Murillo, J. D., Biernacki, J. J., Northrup, S., & Mohammad, A. S. (2017). Biomass pyrolysis kinetics: a review of molecular-scale modeling contributions. *Brazilian Journal of Chemical Engineering*, *34*(1), 1-18.

Nasouri, K., & Shoushtari, A. M. (2018). Fabrication of magnetite nanoparticles/polyvinylpyrrolidone composite nanofibers and their application as electromagnetic interference shielding material. *Journal of Thermoplastic Composite Materials*, *31*(4), 431-446.

Nayak, A., Bhushan, B., Gupta, V., & Sharma, P. (2017). Chemically activated carbon from lignocellulosic wastes for heavy metal wastewater remediation: Effect of activation conditions. *Journal of Colloid and Interface Science*, *493*, 228-240.

Nioua, Y., El Bouazzaoui, S., Achour, M. E., & Costa, L. C. (2017). Modeling microwave dielectric properties of polymer composites using the interphase approach. *Journal of ElEctromagnEtic WavEs and applications*, *31*(14), 1343-1352.

Nishino, T., Matsuda, I., & Hirao, K. (2004). All-cellulose composite. *Macromolecules*, *37*(20), 7683-7687.

Omar, R., Idris, A., Yunus, R., Khalid, K., & Isma, M. A. (2011). Characterization of empty fruit bunch for microwave-assisted pyrolysis. *Fuel*, *90*(4), 1536-1544.

Ooi, C. H., Ang, C. L., & Yeoh, F. Y. (2013). The properties of activated carbon fiber derived from direct activation from oil palm empty fruit bunch fiber. In *Advanced Materials Research*(Vol. 686, pp. 109-117). Trans Tech Publications.

Ooi, C. H., Cheah, W. K., Sim, Y. L., Pung, S. Y., & Yeoh, F. Y. (2017). Conversion and characterization of activated carbon fiber derived from palm empty fruit bunch waste and its kinetic study on urea adsorption. *Journal of environmental management*, *197*, 199-205.

Osman, N. B., Shamsuddin, N., & Uemura, Y. (2016). Activated carbon of oil palm empty fruit bunch (EFB); core and shaggy. *Procedia engineering*, *148*, 758-764.

Ozdemir, I. S ahin, M., Orhan, R., Erdem, M., 2014. Preparation and characterization of activated carbon from grape stalk by zinc chloride activation. *Fuel Process. Technol*, *125*.

Paligová, M., Vilčákova, J., Sáha, P., Křesálek, V., Stejskal, J., & Quadrat, O. (2004). Electromagnetic shielding of epoxy resin composites containing carbon fibers coated with polyaniline base. *Physica A: Statistical Mechanics and its Applications*, *335*(3-4), 421-429.

Paula, A. L. D., Rezende, M. C., & Barroso, J. J. (2011). Experimental measurements and numerical simulation of permittivity and permeability of Teflon in X band. *Journal of Aerospace Technology and Management*, *3*(1), 59-64.

Popovic, Z., & Kuester, E. F. (2013). Principles of RF and Microwave Measurements. *University of Colorado, Electromagnetics Laboratory Department of Electrical and Computer Engineering Campus Box*, *425*, 80309-80425.

Pozar, D. M. (2009). *Microwave engineering*. John Wiley & Sons.

Pratap, V., Soni, A. K., Dayal, S., Abbas, S. M., Siddiqui, A. M., & Prasad, N. E. (2018). Electromagnetic and absorption properties of U-type barium hexaferrite-epoxy composites. *Journal of Magnetism and Magnetic Materials*, *465*, 540-545.

Pramila Devi, D. S., & Sunil, N. K. (2012). *Synthesis, characterization and properties of Conductive elastomeric composites based on Polypyrrole and short Nylon-6 fiber*(Doctoral dissertation, Cochin University of Science and Technology).

Prema, K. H., Kurian, P., Anantharaman, M. R., Suma, M. N., & Joseph, M. (2008). Permittivity characteristics in the X-and S-band frequencies of microwave absorbers based on rubber ferrite composites. *Journal of Elastomers & Plastics*, *40*(4), 331-346.

Qin, F., & Brosseau, C. (2012). A review and analysis of microwave absorption in polymer composites filled with carbonaceous particles. *Journal of applied physics*, *111*(6), 4.

Qing, Y., Wang, X., Zhou, Y., Huang, Z., Luo, F., & Zhou, W. (2014). Enhanced microwave absorption of multi-walled carbon nanotubes/epoxy composites incorporated with ceramic particles. *Composites Science and Technology*, *102*, 161-168.

Qing, Y., Zhou, W., Luo, F., & Zhu, D. (2010). Epoxy-silicone filled with multi-walled carbon nanotubes and carbonyl iron particles as a microwave absorber. *Carbon*, *48*(14), 4074-4080.

Ramli, R., Junadi, N., Beg, M. D., & Yunus, R. M. (2015). Microcrystalline cellulose (MCC) from oil palm empty fruit bunch (EFB) fiber via simultaneous ultrasonic and alkali treatment. *Chemical, Molecular, Nuclear, Materials and Metallurgical Engineering*, *9*(1), 8-11.

Rana, A. K., & Singha, A. S. (2015). Dielectric, flammability and physico-chemical properties of surface functionalized Cannabis indica fibers reinforced composite materials. *Polymer Science Series A*, *57*(2), 221-232.

Ravindren, R., Mondal, S., Nath, K., & Das, N. C. (2019). Prediction of electrical conductivity, double percolation limit and electromagnetic interference shielding effectiveness of copper nanowire filled flexible polymer blend nanocomposites. *Composites Part B: Engineering*, *164*, 559-569.

Ravindren, R., Mondal, S., Nath, K., & Das, N. C. (2019). Synergistic effect of double percolated co-supportive MWCNT-CB conductive network for high-performance EMI shielding application. *Polymers for Advanced Technologies*, *30*(6), 1506-1517.

Rayung, M., Ibrahim, N. A., Zainuddin, N., Saad, W. Z., Razak, N. I. A., & Chieng, B. W. (2014). The effect of fiber bleaching treatment on the properties of poly (lactic acid)/oil palm empty fruit bunch fiber composites. *International journal of molecular sciences*, *15*(8), 14728-14742.

Rostami, M., & Ara, M. H. M. (2019). The dielectric, magnetic and microwave absorption properties of Cu-substituted Mg-Ni spinel ferrite-MWCNT nanocomposites. *Ceramics International*, *45*(6), 7606-7613.

Saba, N., Tahir, P., & Jawaid, M. (2014). A review on potentiality of nano filler/natural fiber filled polymer hybrid composites. *Polymers*, *6*(8), 2247-2273.

Sadiku, M. N. (2000). *Numerical techniques in electromagnetics*. CRC press.

Saini, P., & Arora, M. (2012). Microwave absorption and EMI shielding behavior of nanocomposites based on intrinsically conducting polymers, graphene and carbon nanotubes. In *New Polymers for Special Applications*. IntechOpen.

Saini, P., Arora, M., Gupta, G., Gupta, B. K., Singh, V. N., & Choudhary, V. (2013). High permittivity polyaniline–barium titanate nanocomposites with excellent electromagnetic interference shielding response. *Nanoscale*, *5*(10), 4330-4336.

Saini, P., Choudhary, V., Singh, B. P., Mathur, R. B., & Dhawan, S. K. (2009). Polyaniline–MWCNT nanocomposites for microwave absorption and EMI shielding. *Materials Chemistry and Physics*, *113*(2-3), 919-926.

Salema, A. A., Yeow, Y. K., Ishaque, K., Ani, F. N., Afzal, M. T., & Hassan, A. (2013). Dielectric properties and microwave heating of oil palm biomass and biochar. *Industrial Crops and Products*, *50*, 366-374.

Sherif, E. S. M., Mohammed, J. A., Abdo, H. S., & Almajid, A. A. (2016). Corrosion behavior in highly concentrated sodium chloride solutions of nanocrystalline aluminum processed by high energy ball mill. *International Journal of Electrochemical Science*, *11*(2), 1355-1369.

Shi, Y. D., Yu, H. O., Li, J., Tan, Y. J., Chen, Y. F., Wang, M., ... & Guo, S. (2018). Low magnetic field-induced alignment of nickel particles in segregated poly (l-lactide)/poly (ε-caprolactone)/multi-walled carbon nanotube nanocomposites: Towards remarkable and tunable conductive anisotropy. *Chemical Engineering Journal*, *347*, 472-482.

Shinoj, S., Visvanathan, R., Panigrahi, S., & Kochubabu, M. (2011). Oil palm fiber (OPF) and its composites: A review. *Industrial Crops and products*, *33*(1), 7-22.

Shinoj, S., Visvanathan, R., & Panigrahi, S. (2010). Towards industrial utilization of oil palm fibre: Physical and dielectric characterization of linear low density polyethylene composites and comparison with other fibre sources. *Biosystems engineering*, *106*(4), 378-388.

Shu, R., Zhang, G., Zhang, J., Wang, X., Wang, M., Gan, Y., ... & He, J. (2018). Fabrication of reduced graphene oxide/multi-walled carbon nanotubes/zinc ferrite hybrid composites as high-performance microwave absorbers. *Journal of Alloys and Compounds*, *736*, 1-11.

Sreekumar, P. A., Saiter, J. M., Joseph, K., Unnikrishnan, G., & Thomas, S. (2012). Electrical properties of short sisal fiber reinforced polyester composites fabricated by resin transfer molding. *Composites Part A: Applied Science and Manufacturing*, *43*(3), 507-511.

Surati, M. A., Jauhari, S., & Desai, K. R. (2012). A brief review: Microwave assisted organic reaction. *Archives of Applied Science Research*, *4*(1), 645-661.

Takeda, S., & Naoe, M. (2018). Size optimization for complex permeability measurement of magnetic thin films using a short-circuited microstrip line up to 30 GHz. *Journal of Magnetism and Magnetic Materials*, *449*, 530-537.

Teo, E. Y. L., Muniandy, L., Ng, E. P., Adam, F., Mohamed, A. R., Jose, R., & Chong, K. F. (2016). High surface area activated carbon from rice husk as a high performance supercapacitor electrode. *Electrochimica Acta*, *192*, 110-119.

Teppati, V., Ferrero, A., & Sayed, M. (Eds.). (2013). *Modern RF and microwave measurement techniques*. Cambridge University Press.

Tohidifar, M. R. (2018). Highly-efficient electromagnetic interference shielding and microwave dielectric behavior of a (Bi2O3+ B2O3)-doped MWCNT/BaTiO3 ceramic nanocomposite. *Ceramics International*, *44*(12), 13613-13622.

Vas, J. V., & Thomas, M. J. (2017). Electromagnetic shielding effectiveness of layered polymer nanocomposites. *IEEE Transactions on Electromagnetic Compatibility*, *60*(2), 376-384.

Varshney, S., Ohlan, A., Jain, V. K., Dutta, V. P., & Dhawan, S. K. (2014). Synthesis of ferrofluid based nanoarchitectured polypyrrole composites and its application for electromagnetic shielding. *Materials Chemistry and Physics*, *143*(2), 806-813.

Venkatesh, M. S., & Raghavan, G. S. V. (2005). An overview of dielectric properties measuring techniques. *Canadian biosystems engineering*, *47*(7), 15-30.

Wang, G., Wang, L., Mark, L. H., Shaayegan, V., Wang, G., Li, H., ... & Park, C. B. (2018). Ultralow-threshold and lightweight biodegradable porous PLA/MWCNT with segregated conductive networks for high-performance thermal insulation and electromagnetic interference shielding applications. *ACS applied materials & interfaces*, *10*(1), 1195-1203.

Wang, W., Li, Q., & Chang, C. (2011). Effect of MWCNTs content on the magnetic and wave absorbing properties of ferrite-MWCNTs composites. *Synthetic Metals*, *161*(1-2), 44-50.

Wee, F. H., Soh, P. J., Suhaizal, A. H. M., Nornikman, H., & Ezanuddin, A. A. M. (2009, November). Free space measurement technique on dielectric properties of agricultural residues at microwave frequencies. In *2009 SBMO/IEEE MTT-S International Microwave and Optoelectronics Conference (IMOC)* (pp. 183-187). IEEE.

Wei, L., Che, R., Jiang, Y., & Yu, B. (2013). Study on preparation and microwave absorption property of the core-nanoshell composite materials doped with La. *Journal of Environmental Sciences*, *25*, S27-S31.

Xia, C., Zhang, S., Ren, H., Shi, S. Q., Zhang, H., Cai, L., & Li, J. (2016). Scalable fabrication of natural-fiber reinforced composites with electromagnetic interference shielding properties by incorporating powdered activated carbon. *Materials*, *9*(1), 10.

Xia, C., Yu, J., Shi, S. Q., Qiu, Y., Cai, L., Wu, H. F., ... & Zhang, H. (2017). Natural fiber and aluminum sheet hybrid composites for high electromagnetic interference shielding performance. *Composites Part B: Engineering*, *114*, 121-127.

Xiang, C., Pan, Y., & Guo, J. (2007). Electromagnetic interference shielding effectiveness of multiwalled carbon nanotube reinforced fused silica composites. *Ceramics international*, *33*(7), 1293-1297.

Yakubu, A. (2015). Synthesis and Characterization of Zinc Oxide Polycaprolactone Nanocomposites Using Rectangular Waveguide and Microstrip Techniques. PhD Thesis, Universiti Putra Malaysia.

Yakubu, A., Abbas, Z., Esa, F., & Tohidi, P. (2015). The Effect of ZnO Nanoparticle Filler on the Attenuation of ZnO/PCL Nanocomposites Using Microstrip Line at Microwave Frequency. *International Polymer Processing, 30*(2), 227-232.

Yakubu, A., Abbas, Z., & Hashim, M. (2014). Effect of material thickness on attenuation (dB) of PTFE using finite element method at X-band frequency. *Advances in Materials Science and Engineering, 2014*.

Yee, Y. Y., Ching, Y. C., Rozali, S., Hashim, N. A., & Singh, R. (2016). Preparation and characterization of poly (lactic acid)-based composite reinforced with oil palm empty fruit bunch fiber and nanosilica. *BioResources*, *11*(1), 2269-2286.

Yilmaz, A. C., Ozen, M. S., Sancak, E., Erdem, R., Erdem, O., & Soin, N. (2018). Analyses of the mechanical, electrical and electromagnetic shielding properties of thermoplastic composites doped with conductive nanofillers. *Journal of Composite Materials*, *52*(11), 1423-1432.

Yu, L., Li, B., Sheng, L., An, K., & Zhao, X. (2013). The microwave absorbing properties of SmCo attached single wall carbon nanotube/epoxy composites. *Journal of Alloys and Compounds*, *575*, 123-127.

Zaidi, L., Kaci, M., Bruzaud, S., Bourmaud, A., & Grohens, Y. (2010). Effect of natural weather on the structure and properties of polylactide/Cloisite 30B nanocomposites. *Polymer Degradation and Stability*, *95*(9), 1751-1758.

Zang, H. B., Yan, Q., Zheng, W. G., He, Z., & Yu, Z. Z. (2011). Tough graphene-polymer microcellular foams for electromagnetic interference shielding. ACS Appl. Mater. *Interfaces*, *3*, 918-924.