

Karmjit Singh Sandha

THESIS_ANJU_951606004

 K.S SANDHA
 RAJEEV KR PANDEY
 ABES Engineering College

Document Details

Submission ID**trn:oid::1:3375181640****Submission Date****Oct 16, 2025, 4:35 PM GMT+5:30****Download Date****Oct 16, 2025, 4:41 PM GMT+5:30****File Name****ANJU_TRIPATHI_THESIS_REPORT_16_OCTBER.pdf****File Size****35.2 MB****146 Pages****45,032 Words****256,706 Characters**

13% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

Filtered from the Report

- Small Matches (less than 8 words)

Match Groups

- 429** Not Cited or Quoted 12%
Matches with neither in-text citation nor quotation marks
- 3** Missing Quotations 0%
Matches that are still very similar to source material
- 20** Missing Citation 1%
Matches that have quotation marks, but no in-text citation
- 0** Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

- 8% Internet sources
- 11% Publications
- 1% Submitted works (Student Papers)

Integrity Flags

1 Integrity Flag for Review

- Replaced Characters**
69 suspect characters on 32 pages
Letters are swapped with similar characters from another alphabet.

Our system's algorithms look deeply at a document for any inconsistencies that would set it apart from a normal submission. If we notice something strange, we flag it for you to review.

A Flag is not necessarily an indicator of a problem. However, we'd recommend you focus your attention there for further review.

Match Groups

- 429** Not Cited or Quoted 12%
Matches with neither in-text citation nor quotation marks
- 3** Missing Quotations 0%
Matches that are still very similar to source material
- 20** Missing Citation 1%
Matches that have quotation marks, but no in-text citation
- 0** Cited and Quoted 0%
Matches with in-text citation present, but no quotation marks

Top Sources

- 8% Internet sources
- 11% Publications
- 1% Submitted works (Student Papers)

Top Sources

The sources with the highest number of matches within the submission. Overlapping sources will not be displayed.

- 1** Internet
link.springer.com 2%
- 2** Publication
Anju Tripathi, Karmjit Singh Sandha. "Impact of Thickness and wt% on the Dielect... 2%
- 3** Publication
Anju Tripathi, Karmjit Singh Sandha. "Broad microwave absorption bandwidth an... 2%
- 4** Internet
www.researchgate.net <1%
- 5** Internet
worldwidescience.org <1%
- 6** Internet
www.science.gov <1%
- 7** Internet
krclib.ncl.res.in <1%
- 8** Publication
Saran Srihari Sripada Panda, Suman Gandhi, Trilochan Panigrahi, Saidi Reddy Parn... <1%
- 9** Publication
Nidya Chitraningrum, Resti Marlina, Ria Yolanda Arundina, Ester Rimma Suryani ... <1%
- 10** Internet
www.mdpi.com <1%

11	Publication	Salim H. Siddiki, Chandan Kumar Maity, Sumanta Sahoo. "Advances in microwave...	<1%
12	Publication	Hitender Gupta, Rajesh Khanna, Mayank Kumar Rai. "Metal-free MWCNT and sug...	<1%
13	Publication	Lecture Notes in Electrical Engineering, 2015.	<1%
14	Internet	pubs.rsc.org	<1%
15	Publication	"Carbon-Based Nanocomposites for Sustainable Applications, Volume II", Springe...	<1%
16	Publication	Geetika Verma, Kamla Prasan Ray. "Design, Fabrication and Characteristics of Eco...	<1%
17	Publication	Anju, Raghvendra Singh Yadav, Petra Pötschke, Jürgen Pionteck et al. " High-Perf...	<1%
18	Publication	Sahil Sharma, Saidi Reddy Parne, Saran Srihari Sripada Panda, Suman Gandhi. "Pro...	<1%
19	Internet	theses.hal.science	<1%
20	Internet	openaccess.city.ac.uk	<1%
21	Internet	hal.univ-lorraine.fr	<1%
22	Publication	L. F. Chen, C. K. Ong, C. P. Neo, V. V. Varadan, V. K. Varadan. "Microwave Electroni...	<1%
23	Publication	Raghvendra Singh Yadav, Ivo Kuřitka. "Recent advances on outstanding microwa...	<1%
24	Publication	Sahil Sharma, Suman Gandhi, Saran Srihari Sripada Panda, Saidi Reddy Parne. "Exp...	<1%

25	Student papers	University of Central Florida	<1%
26	Internet	assets.researchsquare.com	<1%
27	Publication	Pawandeep Kaur, S. Bindra Narang, Shalini Bahel. "Complex permittivity, comple...	<1%
28	Internet	apps.dtic.mil	<1%
29	Internet	"Wave-Absorbing Properties of Multi-Walled Carbon Nanotubes Reinforced Ceme...	<1%
30	Internet	ora.ox.ac.uk	<1%
31	Publication	Shoufeng Xue, Huixiang Wang, Weiyi Wang, Wanxi Li, Jianghong Wu, Yingfen Wa...	<1%
32	Internet	dataintelo.com	<1%
33	Internet	tel.archives-ouvertes.fr	<1%
34	Internet	www.jkcs.or.kr	<1%
35	Publication	Haitao Bai, Pengfei Yin, Xu Lu, Limin Zhang, Wenjuan Wu, Xing Feng, Jian Wang, Ji...	<1%
36	Internet	fastercapital.com	<1%
37	Internet	scholarcommons.usf.edu	<1%
38	Internet	www.tandfonline.com	<1%

39	Publication	Jiqi Wang, Fei Wu, Baoliang Zhang. "Preparation and microwave absorption prop...	<1%
40	Internet	courses.chem.indiana.edu	<1%
41	Internet	ntnuopen.ntnu.no	<1%
42	Student papers	Jawaharlal Nehru Technological University	<1%
43	Publication	Lawal Lanre Adebayo, Hassan Soleimani, Noorhana Yahya, Zulkifly Abbas, Fatai A...	<1%
44	Publication	Xueping Wu, Aoxuan Dong, Shilong Xu, Haixia Huang, Kesong Xiao, Ying Jiang, Ku...	<1%
45	Publication	Yi-Huan Lee, Lyu-Ying Wang, Chung-Ying Tsai, Chia-Wei Lee. " Self-Healing Nanoc...	<1%
46	Publication	Ying Liu, Zhongquan Zhang, Songtao Xiao, Chengwen Qiang, Liangliang Tian, Jinc...	<1%
47	Internet	scholarworks.uark.edu	<1%
48	Publication	Mora, N., P. Savi, M. Giorcelli, and F. Rachidi. "Analysis and modeling of epoxy/M...	<1%
49	Publication	R.S. Chavan, S.R. Chavan. "Microwave Baking in Food Industry: A Review", Interna...	<1%
50	Internet	prism.ucalgary.ca	<1%
51	Publication	Shiqi Zheng, Tao Jiang, Xinyu Wei, Qinyu Cai, Chi Chen, Gang Fang, Chuyang Liu. "...	<1%
52	Publication	X.G. Liu, D.Y. Geng, H. Meng, W.B. Cui, F. Yang, D.J. Kang, Z.D. Zhang. "Microwave ...	<1%

53	Publication	Juan Li, Lei Wang, Dong Zhang, Yue Qu, Guangming Wang, Ge Tian, Anhua Liu, H...	<1%
54	Publication	Moodhy S Al-Athel, Robert G Jagger. "Effect of test method on the bond strength ...	<1%
55	Internet	www.cambridge.org	<1%
56	Internet	www.degruyter.com	<1%
57	Publication	Chandi Charan Dey, Sukhendu Sadhukhan, Ayan Mitra, Madhumita Dalal, Anirba...	<1%
58	Publication	Jiaming Xu, Long Xia, Juhua Luo, Siru Lu, Xiaoxiao Huang, Bo Zhong, Tao Zhang, G...	<1%
59	Publication	Mengjia Wei, Lei Wang, Sajjad Ur Rehman, Xianguo Luo, Yifeng Hu, Changcai Che...	<1%
60	Publication	Rishabha Malviya, Selcan Karakuş, Sonali Sundram, Sathvik Belagodu Sridhar. "Ca...	<1%
61	Publication	Xiaojun Zeng, Guangming Jiang, Lingyu Zhu, Chenyu Wang, Meng Chen, Ronghai ...	<1%
62	Internet	arrow.tudublin.ie	<1%
63	Internet	etheses.bham.ac.uk	<1%
64	Publication	"Nanostructured Materials for Environmental Applications", Springer Science and...	<1%
65	Publication	Aditi Mishra, Anshika Verma, Dharmendra Singh, Nikhil Dhawan. "Turning Trash i...	<1%
66	Publication	Da Li, Haoyan Liao, Hiroaki Kikuchi, Tong Liu. "Microporous Co@C Nanoparticles ...	<1%

67	Publication	Mohammad Karamouz, Ali Moridi. "Urban Water Engineering and Management", ...	<1%
68	Publication	Norazwina Zainol, Nurfarhana Mustafa, Nor Hazwani Aziz, Azahani Natasha Azm...	<1%
69	Student papers	Uttar Pradesh Technical University	<1%
70	Internet	epa.oszk.hu	<1%
71	Internet	mdpi-res.com	<1%
72	Publication	Nik Nurfatmah Pz Nik Pauzi, Nur Aainaa Syahirah Ramli, Chung-Hung Chan, Moh...	<1%
73	Internet	www.diplomarbeiten24.de	<1%
74	Student papers	University Tun Hussein Onn Malaysia	<1%
75	Publication	Yahong Zhang, Lu Zhang, Haoxu Si, Yi Zhang, Cuiping Li, Lei Zhang, Jingwei Zhang...	<1%
76	Internet	1library.org	<1%
77	Student papers	Anna University	<1%
78	Student papers	Indian Institute of Technology, Kharagpure	<1%
79	Publication	Kamlesh V. Chandekar, Mohd Shkir, Baskaran Palanivel, Zubair Ahmad, H. Algarni...	<1%
80	Student papers	National Institute of Pharmaceutical Education and Research	<1%

81	Student papers	Sharda University	<1%
82	Internet	www.alldatasheetde.com	<1%
83	Student papers	Higher Education Commission Pakistan	<1%
84	Publication	Leila Akbarzadeh Gholidizchi, Morad Ebrahimkhas, Hossein Hooshyar. "GO@CNT...	<1%
85	Internet	mgvmgsr.kbhgroup.in	<1%
86	Internet	www.scielo.br	<1%
87	Student papers	Birla Institute of Technology and Science Pilani	<1%
88	Publication	Deeksha Gupta, Prabhakar Kumar, Ashish Dubey, Abhishek Kumar. "Developmen...	<1%
89	Student papers	Galgotias University, Greater Noida	<1%
90	Student papers	Librarian NITT	<1%
91	Publication	P. Siva Nagasree, K. Ramji, M. K. Naidu, T. C. Shami. "X-band radar-absorbing stru...	<1%
92	Publication	Saran Srihari Sripada Panda, Suman Gandhi, Trilochan Panigrahi, Saidi Reddy Parn...	<1%
93	Publication	Soumya Sundar Pattanayak, Shahedul Haque Laskar, Swagatadeb Sahoo. "Investi...	<1%
94	Student papers	University of Johannesburg	<1%

95	Publication	Y.S. Lee, F.H. Wee, K.Y. You, Z. Liyana et al. "Study of single layer microwave absor...	<1%
96	Publication	Zhengchen Wu, Donggui Tan, Ke Tian, Wei Hu, Jingjing Wang, Mengxing Su, Lei Li....	<1%
97	Internet	datapdf.com	<1%
98	Internet	edoc.unibas.ch	<1%
99	Internet	thesis.library.caltech.edu	<1%
100	Internet	www.cell.com	<1%
101	Internet	www.coursehero.com	<1%
102	Publication	Geetika Verma, S. Datar, K. P. Ray. "Performance Analysis of Absorption Propertie...	<1%
103	Publication	S. Somasundaram, S. Muthukumar, A. Sahaya Anselin Nisha, G. Arul Jothi. "A nove...	<1%
104	Publication	Soumya Sundar Pattanayak, S. H. Laskar, Swagatadeb Sahoo. "Microwave absorp...	<1%
105	Publication	Yang, Xin-Chun, Rui-Jiang Liu, Xiang-Qian Shen, Fu-Zhan Song, Mao-Xiang Jing, an...	<1%
106	Publication	Yusuf Sani, Raba'ah Syahidah Azis, Ismayadi Ismail, Yazid Yaakob, J. Mohammed. ...	<1%
107	Publication	Zhijiang Wang, Lina Wu, Jigang Zhou, Wei Cai, Baozhong Shen, Zhaohua Jiang. "M...	<1%
108	Internet	arxiv.org	<1%

109	Internet	khazna.ku.ac.ae	<1%
110	Internet	www.jpier.org	<1%
111	Internet	www.researchsquare.com	<1%
112	Publication	Azizurrahman Ansari, Mohammad Jaleel Akhtar. "Co/graphite based light weigh...	<1%
113	Publication	Jialiang Liu, Dongwei Xu, Ping Chen, Qi Yu, Hongfang Qiu, Xuhai Xiong. "Solvother...	<1%
114	Publication	Jiu Rong Liu. "Magnetic and electromagnetic wave absorption properties of α -Fe/...	<1%
115	Publication	Lee Yeng Seng, Soh Ping Jack, You Kok Yeow, Wee Fwen Hoon, Lee Chia Yew, Gan ...	<1%
116	Publication	Ozyoldas, Oguz. "Production and Characterisation of Bi _{1.5} Zn _{0.92} Nb _{1.5} O _{6.92} Pyro...	<1%
117	Internet	aemjournal.org	<1%
118	Internet	core.ac.uk	<1%
119	Internet	crescent.education	<1%
120	Internet	discovery.researcher.life	<1%
121	Internet	ejournal2.undip.ac.id	<1%
122	Internet	os.zhdk.cloud.switch.ch	<1%

123	Internet	prfree.org	<1%
124	Internet	users.monash.edu.au	<1%
125	Publication	"Fundamental and Applied Nano-Electromagnetics II", Springer Science and Busi...	<1%
126	Publication	Azizurrahman Ansari, Mohammad Jaleel Akhtar. "Investigation on electromagn...	<1%
127	Publication	Cao, M.S.. "The effects of temperature and frequency on the dielectric properties,...	<1%
128	Publication	E. Roumeli, A. Markoulis, K. Chrissafis, A. Avgeropoulos, D. Bikiaris. "Substantial e...	<1%
129	Publication	Gopal Datt, Chetan Kotabage, A. C. Abhyankar. " Ferromagnetic resonance of NiC...	<1%
130	Publication	Ismayadi Ismail, Khamirul Amin Matori, Zulkifly Abbas, Muhamad Misbah Muha...	<1%
131	Publication	Sakshey Mittal, R.K. Mondal, B.N. Kaul, K.A. Dubey, Y.K. Bhardwaj. "Gamma radiat...	<1%
132	Publication	Shan Gao, Guang-Sheng Wang, Lin Guo, Shu-Hong Yu. "Tunable and Ultraefficient...	<1%
133	Publication	Sumit Kumar, Rajan Walia, Ashwani Kumar, Vivek Verma. "Hybrid structure of M...	<1%
134	Publication	Xiaosi Qi, Yu Deng, Wei Zhong, Yi Yang, Chuan Qin, Chaktong Au, Youwei Du. " Co...	<1%
135	Publication	Xiaozhen He, Ilkka Rytöluoto, Rafal Anyszka, Amirhossein Mahtabani et al. "Surfa...	<1%
136	Publication	Yali Qi, Pengfei Yin, Limin Zhang, Jian Wang, Xing Feng, Kaiming Wang, Liang Zha...	<1%

137	Publication	Yan Cheng, Wei Meng, Zhaoyong Li, Huanqin Zhao, Jieming Cao, Youwei Du, Guan...	<1%
138	Publication	Yan Wang, Pengyu Zang, Dan Yang, Rui Zhang, Shili Gai, Piaoping Yang. "The fund...	<1%
139	Publication	Yichao Yin, Xiaofang Liu, Xiaojun Wei, Ya Li, Xiaoyu Nie, Ronghai Yu, Jianglan Shui...	<1%
140	Internet	dyuthi.cusat.ac.in	<1%
141	Internet	eprints.kku.edu.sa	<1%
142	Internet	oa.upm.es	<1%
143	Internet	pdfcoffee.com	<1%
144	Internet	repository.tudelft.nl	<1%
145	Internet	theses.fr	<1%
146	Internet	uia.brage.unit.no	<1%
147	Internet	www.coolest-gadgets.com	<1%
148	Internet	www.espublisher.com	<1%
149	Publication	Özenler, Sezer. "Preparation of Nanostructured Interface by Polymer Grafting on ...	<1%

CHAPTER 1

INTRODUCTION

1.1. Overview

Microwaves, belonging to the electromagnetic spectrum with wavelengths between 1 millimetre and 1 meter and their frequencies range from about 300 MHz to 300 GHz [1], have become important in modern technology. Their uses cover various fields, such as home domestic appliances, medical technology, communication networks, and defence systems, especially within the frequency range of 1 to 50 GHz [2]. Advancements in wireless communication and the development of compact electronic systems have significantly influenced modern technology, where microwave applications provide reliable connectivity and operational efficiency in domains such as radar, satellite communication, mobile telephony, wireless networking, and point-to-point transmission. The exponential growth of these technologies has made human life increasingly dependent on electronic and wireless devices. Gadgets like smartphones, laptops, digital computers, Bluetooth-enabled instruments, and Wi-Fi networks are now deeply integrated into our daily activities. Consequently, individuals are continuously exposed to radio frequency (RF) radiation both directly, through the active use of such devices, and indirectly by residing near infrastructure such as cellular towers, broadcasting antennas, and base stations.

However, the widespread utilization of the microwave spectrum has led to an unintended consequence, electromagnetic interference (EMI) pollution. EM pollution refers to the unwanted or excessive electromagnetic radiation emitted by communication systems and electronic devices into the surrounding environment. The implications of this phenomenon are complicated. On one hand, it reduces the efficiency and operational lifespan of sensitive electronic equipment by causing interference, overheating, or premature failure. On the other hand, and more critically, it poses significant risks to human health. A growing body of studies and reports suggests that long-term exposure to electromagnetic radiation can induce a wide spectrum of health issues [3]. These range from relatively common problems such as headaches, fatigue, and sleep disturbances, to more severe complications including nausea, impaired cognitive performance, and neurological disorders. Furthermore, continued exposure has also been associated with chronic conditions like tinnitus, depression, and, in extreme cases, brain tumors [4].

Considering the adverse impacts, it is crucial to mitigate electromagnetic pollution, with microwave absorber materials (MAMs) offering a highly effective and sustainable solution [5]. These materials absorb incoming electromagnetic waves and convert them into heat, reducing reflections and limiting interference[6]. The research focus on MAMs gained momentum in the 1990s due to increasing governmental regulations and international standards aimed at limiting electromagnetic emissions. Apart from their role in civil and industrial sectors, microwave absorbers have significant importance in stealth technology, which aims to cover military assets such as aircraft, missiles, ships, and ground vehicles from enemy radar detection systems. Historically, the military was among the first sectors to adopt microwave absorbing coatings; for example, during World War II, the U.S. developed Halpern Anti-Radar Paint (HARP), a composite based on carbon black incorporated in rubber, disc-shaped aluminium flakes, and barium titanate (BaTiO_3) for radar evasion [7].

Furthermore, the global market for microwave absorbers reflects their growing importance across multiple industries. According to recent industry research, the global market for microwave absorbers was estimated to be worth USD 365.6 million in 2023. As shown in Figure 1.1, it is expected to increase at a compound annual growth rate (CAGR) of 6.1% from 2024 to 2032, reaching USD 617.4 million by the end of 2032 [8]. This growth trend is largely driven by the increasing demand for EMI shielding in consumer electronics, automotive electronics, defence applications, and telecommunication infrastructure, all of which require advanced solutions for reducing electromagnetic interference and ensuring system stability.

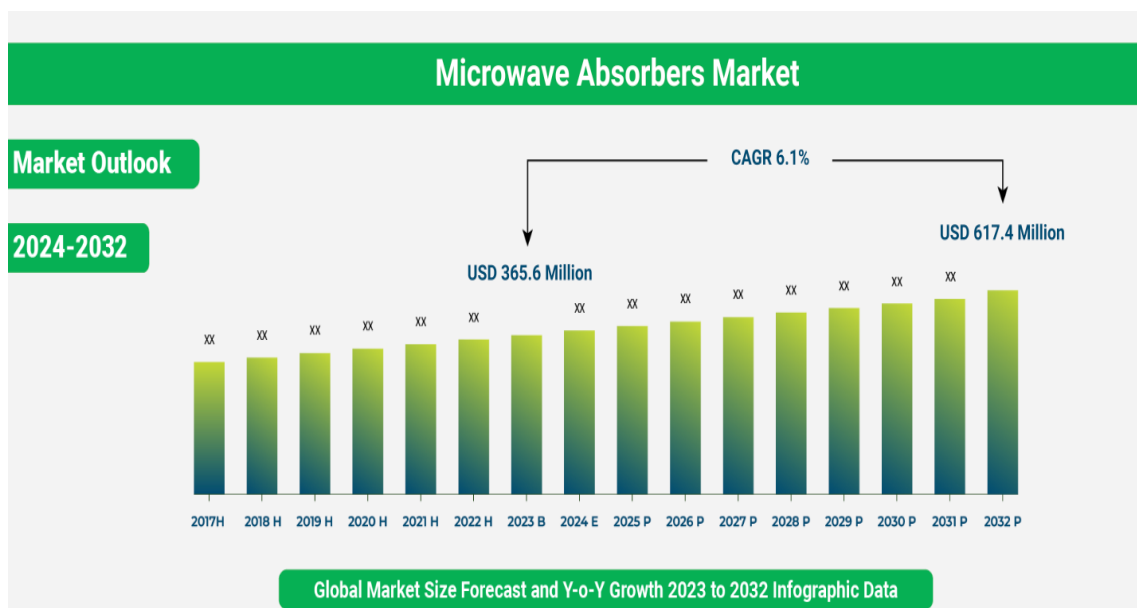


Figure 1.1 Global Microwave Absorbers Market Size Forecast (2024–2032) with CAGR Growth [8]

Ongoing research efforts continue to focus on designing and developing high-performance MAMs that effectively suppress EMI while ensuring compatibility with modern devices. The sources of EMI can generally be classified into natural, unintentional, and intentional radiators, each exhibiting unique characteristics such as unknown polarization, random directionality, and broad bandwidth. Figure 1.2 illustrates these sources and demonstrates how microwave absorbers function to create EMI-free zones through mechanisms such as wave absorption, heat dissipation, and electromagnetic shielding.

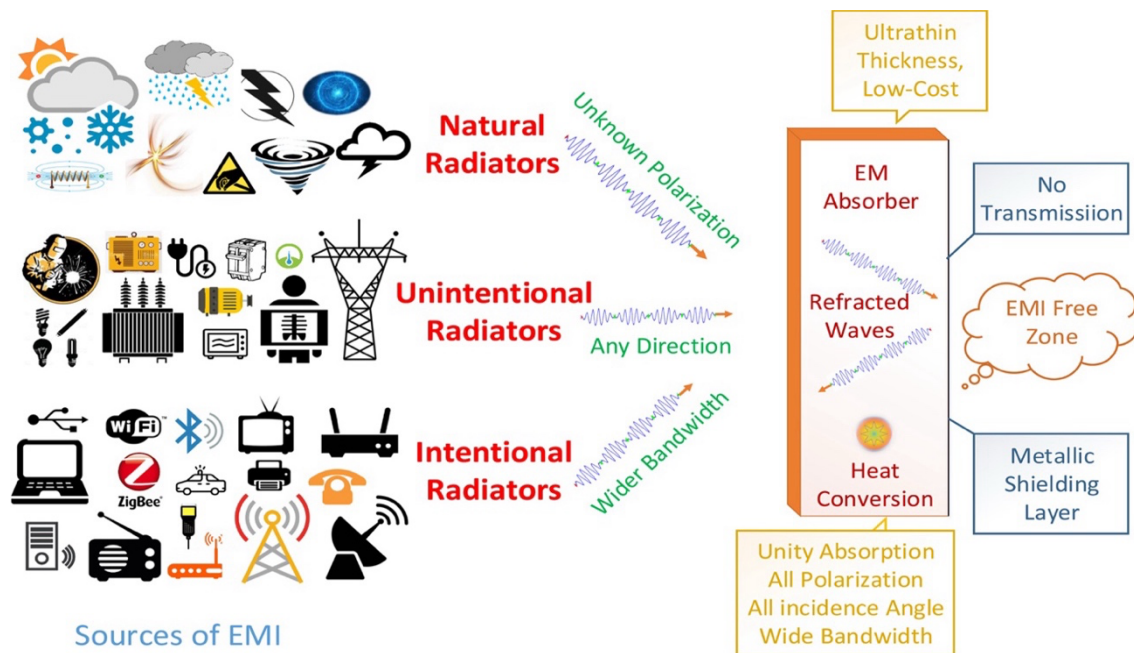


Figure 1.2 Sources of EMI and mitigation using a Microwave absorber for creating EMI-free zones.

1.2 Microwave absorber material

Microwave absorber materials (MAMs) are specifically designed to absorb or weaken electromagnetic waves within the frequency range of 300 MHz to 300 GHz. These materials play a crucial role in minimizing undesired reflections, reducing radar visibility, and decreasing electromagnetic interference. Applications for MAMs include electronic products, healthcare equipment, wireless communication, defence systems, aerospace, and radar systems in transportation.

With the growing use of wireless communication technologies (e.g., 5G, satellite communication, and IoT devices), the demand for effective MAMs is increasing. Without these materials, unwanted electromagnetic waves can lead to signal distortion, interference in

communication systems, and potential malfunctions in sensitive equipment. Therefore, the development of efficient, lightweight, broadband, and eco-friendly microwave absorbers has become an important area of research.

1.2.1 Working Principle of Microwave Absorber Material

The basic principle behind microwave absorbers is that incident electromagnetic energy is transformed into another form of energy, mainly heat, through mechanisms such as dielectric loss, magnetic loss, or a combination of both, as demonstrated in Figure 1.3 [9].

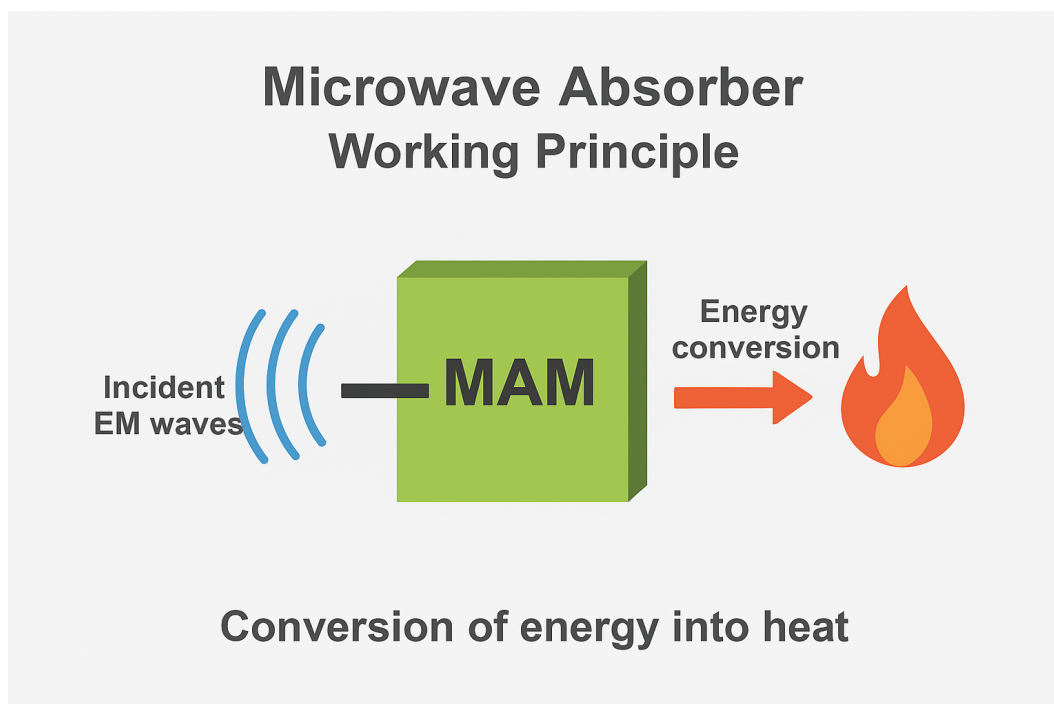


Figure 1.3 Operating principle of Microwave absorber material

When a microwave signal interacts with the surface of a microwave absorber material, three main interactions occur:

1.2.1.1 Reflection

The surface of the material reflects back some of the incident electromagnetic wave [10]. The goal of an effective absorber is to minimize reflection, ensuring that maximum energy penetrates the absorber.

1.2.1.2 Absorption (Attenuation)

Part of the microwave energy enters the material and is transformed into heat or other energy forms through dielectric and magnetic losses, which largely determine the absorber's effectiveness.

1.2.1.3 Transmission

Some microwave energy may pass through the material, but an effective absorber minimizes this transmission, often by adjusting thickness or using a backing plate [11].

1.2.1.4 Conversion to Heat

The absorbed electromagnetic energy is ultimately dissipated as heat within the material through internal friction, eddy currents, and molecular vibrations. This conversion reduces the amount of energy reflected or transmitted, making the absorber effective [12].

1.2.2 Key Performance Indicators of MAM

The key performance of MAMs is primarily calculated using Reflection Loss (RL), which indicates how much incident electromagnetic energy the material has absorbed and is measured in decibels (dB) [13]. A lower RL value indicates better absorbing efficiency. In practical terms, an RL of -10 dB or lower means the material absorbs at least 90% of the incident energy, which is considered the minimum requirement for effective microwave absorption. An RL of -20 dB indicates roughly 99% wave absorption, whereas values below -40 dB reflect exceptional absorption, making the material ideal for applications like stealth technology and EMI reduction [14]. Reflection loss (RL) is evaluated using transmission line theory, which analyzes how the absorber's input impedance matches the characteristic impedance of free space to optimize wave absorption. In addition to RL, other critical performance indicators include absorption bandwidth (frequency range over which RL remains below -10 dB), material thickness, impedance matching, and thermal and mechanical stability [15]. An ideal microwave absorber should achieve strong absorption, a broad bandwidth, maintain a lightweight structure, ensure environmental sustainability, and be cost-effective.

1.2.3 Absorption Mechanisms in Microwave Materials

Microwave absorption in absorber materials primarily arises from interactions between electromagnetic waves and the material, converting EM energy into heat. Key mechanisms include dielectric loss, magnetic loss, conduction loss, and interfacial polarization, with impedance matching often working concurrently to improve overall absorption performance [16,17]. Below is a detailed explanation:

1.2.3.1 Dielectric Loss

When polar molecules and charge carriers in the material interact with the microwave's electric field, dielectric loss occurs. Polarization relaxation happens when an alternating

1 electromagnetic field is applied to a material. In this process, the internal dipoles of the material
8 attempt to align themselves with the rapidly changing electric field. This ongoing realignment
of dipoles creates friction and results in energy loss, which is primarily emitted as heat [18].
This continuous realigning of dipoles generates friction and energy dissipation in the form of
heat. Additionally, dipolar polarization, electronic polarization, and ionic polarization
contribute to dielectric loss. Conductive fillers like carbon nanotubes, graphene, and similar
materials are known to exhibit significant dielectric loss.

1.2.3.2 Magnetic Loss

1 When magnetic dipoles in absorber material interact with the magnetic field component of
electromagnetic waves, magnetic loss occurs [19]. This mechanism is dominant in materials
that contain magnetic substances such as ferrites, metal oxides, or magnetic nanoparticles.
Magnetic loss primarily results from three mechanisms. The first mechanism is natural
resonance, where magnetic domains rotate in response to the applied magnetic field, causing
energy dissipation. The second mechanism is eddy current loss, which occurs due to induced
currents that generate heat. The third mechanism is domain wall resonance, which arises from
the oscillation of domain walls under alternating magnetic fields [20]. These magnetic
interactions are highly effective in attenuating microwaves, particularly at lower frequency
ranges, and are often combined with dielectric loss in composite absorbers

1.2.3.3 Conduction Loss

Conduction loss occurs when a material has free-moving electrons, as in conductive fillers like
carbon nanotubes (CNTs) or graphene. Electrons fluctuate and generate current when exposed
to an electromagnetic field, which results in Joule heating [21]. This mechanism is highly
effective in carbon-based composites and conductive polymer absorbers.

1.2.3.4 Interfacial Polarization

Interfacial polarization occurs at the boundaries between different phases in composite
materials, such as between a dielectric matrix and conductive or magnetic fillers. When EM
waves pass through the composite, charges accumulate at these interfaces due to differences in
conductivity and permittivity, creating localized electric fields. The relaxation of these
accumulated charges contributes to energy dissipation.

1.2.3.5 Impedance Matching

Impedance matching is necessary for efficient absorption, even if it is not a loss mechanism.
132 More waves enter the material rather than reflecting when the absorber impedance gets close

to that of free space ($\sim 377 \Omega$), which makes dielectric, magnetic, and conduction losses more effective [22].

1.3 Desired properties of Microwave Absorber

Microwave absorbers intended for practical applications must exhibit a combination of properties to ensure high efficiency, durability, and adaptability to different operational environments. The desired properties are as follows:

1.3.1 Lightweight

Microwave absorbers are often used in applications like aerospace, satellites, and military stealth systems, where weight reduction is critical for fuel efficiency and operational performance. Heavy materials increase load and energy consumption, making lightweight absorbers highly desirable. Lightweight materials also enable easier handling and integration into various devices without compromising performance. Typically, carbon-based materials (CNTs, graphene) and biomass-derived materials are favoured for their low density combined with strong absorption properties.

1.3.2 Broadband Absorption

Microwave absorbers must perform effectively over a broad frequency range. For instance, in radar and communication systems, X-band (8.2–12.4 GHz) absorbers need to ensure consistent attenuation across the entire band [23]. Broadband absorption ensures that the material can suppress electromagnetic interference (EMI) from multiple sources and prevent radar detection over varying frequencies. Achieving broadband performance usually involves combining dielectric and magnetic loss mechanisms or designing multi-layered composites with impedance matching.

1.3.3 Thin Thickness with Strong Absorption

Modern applications demand thin and compact absorber layers without sacrificing performance. A thinner absorber reduces weight and volume, making it ideal for integration into stealth coatings, electronic devices, and lightweight structures. The main challenge is achieving strong absorption $RL \leq -10$ dB at minimal thickness, which requires optimizing material composition, microstructure, and impedance matching for maximum energy dissipation [24].

1.3.4 Environmental Friendliness and Cost-Effectiveness

Traditional microwave absorbers often use expensive or hazardous chemicals (e.g., ferrites, metallic powders), which pose environmental and economic concerns. The use of biomass-derived materials (e.g., banana leaves, sugarcane bagasse) offers a sustainable and low-cost alternative, reducing dependency on synthetic chemicals and minimizing waste. Environmentally friendly absorbers also support global initiatives toward green technologies and circular economy principles by utilizing agricultural waste for high-value applications.

1.3.5 Thermal Stability and Mechanical Strength

Microwave absorbers are frequently exposed to harsh environments, such as high temperatures in aerospace or defence applications. Therefore, thermal stability ensures that the material maintains its electromagnetic and structural integrity under elevated temperatures. Similarly, good mechanical strength prevents cracking, delamination, or deformation under stress, vibrations, or external forces. Materials like metal oxides, carbides, and high-entropy ceramics exhibit excellent thermal stability, while composite structures with polymers or resins can provide flexibility and mechanical robustness [25].

1.4 Shape of Microwave Absorber Material

The design and geometry of microwave absorber materials (MAMs) significantly influence their absorption performance across different frequency ranges. Various shapes are employed to optimize impedance matching, minimize reflection, and enhance absorption bandwidth. The most common shapes are explained below:

1.4.1 Pyramidal Absorbers

In microwave applications, pyramidal absorbers are frequently chosen due to their exceptional broadband absorption capabilities [26]. These structures feature a broad base and a pointed apex, forming a gradual taper from the base to the tip. This geometry ensures a smooth transition of impedance from free space to the absorber material, effectively reducing reflection and enhancing electromagnetic wave penetration. The gradual taper minimizes impedance mismatch, allowing the incident wave to be absorbed and converted into heat energy inside the material. Pyramidal absorbers are frequently used to lower radar cross-section (RCS) and conduct electromagnetic compatibility testing in anechoic chambers. Their ability to provide efficient absorption over a wide range of frequencies makes them ideal for defence, aerospace, and testing environments, as shown in Figure 1.4.

1.4.2 Wedge-Shaped Absorbers

Wedge absorbers consist of long, tapered structures that gradually decrease in thickness toward the tip. This design helps in reducing reflections by gradually changing the impedance, similar to pyramidal absorbers, but over a narrower bandwidth. Wedge absorbers are particularly useful in EMI suppression environments and for absorbing directional incident waves in microwave testing chambers. They are often combined with pyramidal absorbers to enhance overall absorption performance [27].



Figure 1.4 Pyramidal-shaped microwave absorber.



Figure 1.5 Wedge-Shaped Microwave Absorber

1.4.3 Flat Sheet (Planar) Absorbers

Flat sheet absorbers are designed in the form of thin, planar layers that can be easily applied to surfaces, as shown in Figure 1.6. These sheets are lightweight and flexible, making them ideal for surface coating applications such as aircraft bodies, vehicles, and walls of EMI-shielded

rooms. Flat sheet absorbers typically rely on dielectric loss, magnetic loss, or a combination of both to attenuate electromagnetic waves [28]. They are widely used in stealth technology and portable electronic devices for reducing electromagnetic interference.



Figure 1.6 Flat Sheet (Planar) Microwave Absorbers

1.4.4 Honeycomb and Foam Absorbers

Honeycomb and foam absorbers are lightweight structures made of dielectric or magnetic materials combined with air cavities to reduce density without compromising absorption performance. The honeycomb design allows electromagnetic waves to penetrate deeply and dissipate energy within the structure. The honeycomb structure microwave absorber is shown in Figure 1.7. These absorbers are frequently utilized in automotive and aerospace applications where high absorption efficiency and weight reduction are crucial [29]. Foam absorbers are also suitable for high-temperature environments due to their thermal stability.

1.4.5 Conformal Absorbers

Conformal absorbers are custom-designed to fit complex and curved surfaces, such as the body of aircraft, ships, or missiles. Unlike flat sheets or rigid pyramidal structures, conformal absorbers can be molded or laminated to achieve a seamless surface coverage. These absorbers are primarily used in stealth applications to minimize radar signatures without altering the aerodynamics of the platform [30]. They provide effective absorption across targeted frequency ranges while maintaining the shape and performance of the host structure, as shown in Figure 1.8.



Figure 1.7 Honeycomb and Foam Microwave Absorbers

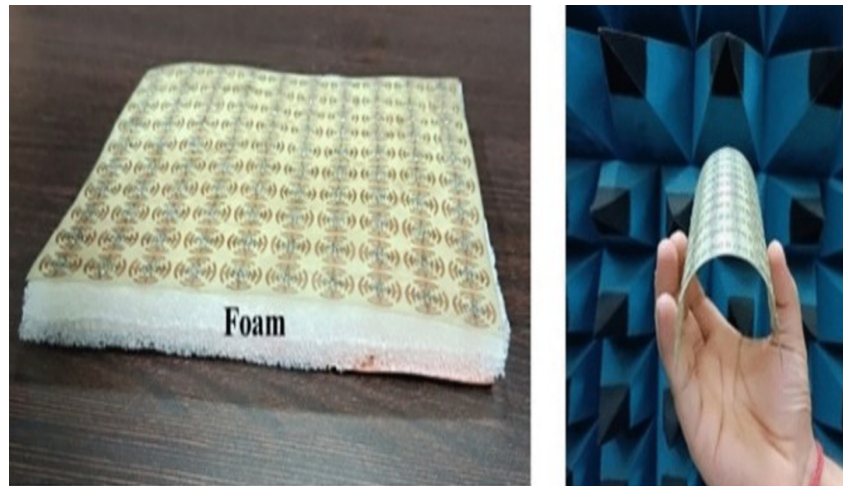


Figure 1.8 Conformal Microwave Absorbers

1.5 TYPES OF MICROWAVE ABSORBER

MAMs can be classified based on their structure, content, and absorption mechanisms, as illustrated in Figure 1.9 [31]. Each category of material has distinct electromagnetic properties that influence its absorption performance. The following subsections will discuss the various types of MAMs, their characteristics, applications, and limitations.

1.5.1 Magnetic Materials

Magnetic materials such as ferrites (including Fe_3O_4 and nickel-zinc ferrite) and metals like iron, cobalt, and nickel are widely utilized because of their strong magnetic loss properties. These characteristics are brought about by processes such as eddy current loss, exchange resonance, and natural resonance [18]. In particular, these materials are effective at absorbing

electromagnetic radiation in low-frequency microwave bands like L, S, and X. They are frequently used in applications like antenna systems, EMI shielding, and radar stealth [32].

1.5.1.1. Limitations of Magnetic Materials

- The high density and weight of these materials render them unsuitable for lightweight aerospace applications.
- The absorption bandwidth is narrow at high frequencies.
- Limited flexibility in coatings and wearable devices.

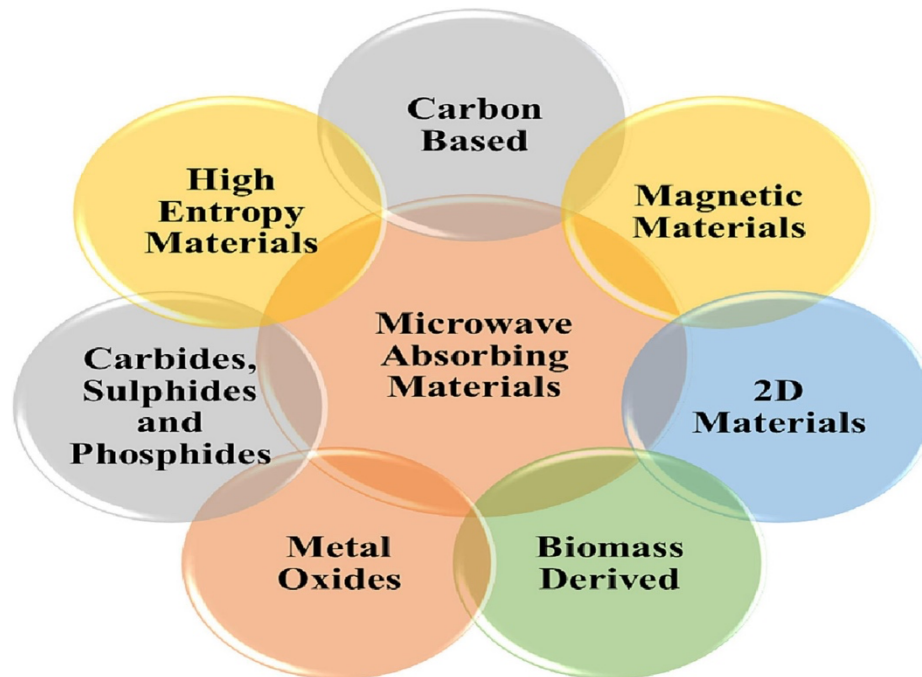


Figure 1.9 Types of Microwave Absorber Materials

1.5.2 2D Materials

2D materials such as graphene, MXenes, and MoS₂ possess unique layered structures, large surface areas, and adjustable electronic properties. These characteristics promote interfacial polarization, dipole relaxation, and conduction loss, leading to significant dielectric absorption. Their flexibility and light weight also make them perfect for flexible absorber designs and thin-film coatings, which can be used in stealth and next-generation EMI shielding applications [33].

1.5.2.1. Limitations of 2D Materials

- High production cost (e.g., graphene synthesis is expensive and complex).
- Agglomeration problems can reduce the effective surface area and absorption efficiency.

- Surface functionalization or hybridization with other materials is often necessary to achieve impedance matching.

1.5.3 Metal Oxides

Metal oxides such as Fe_2O_3 , Co_3O_4 , TiO_2 , and ZnO demonstrate both dielectric and magnetic loss mechanisms, making them effective absorbers of electromagnetic (EM) waves. They are appropriate for extreme conditions, like those found in aerospace and high-temperature applications, due to their exceptional thermal stability and chemical resistance [34]. These materials absorb EM waves through mechanisms like dipole polarization and magnetic resonance. Additionally, they are often combined with conductive materials to enhance the absorption bandwidth.

1.5.3.1. Limitations of Metal Oxides

- Low electrical conductivity restricts dielectric loss, which in turn decreases absorption efficiency.
- High-temperature processing is required, which increases the fabrication cost.
- When used alone, they offer a narrow absorption bandwidth and need to be combined with other elements to enhance their performance

1.5.4 Carbides, Sulphides, and Phosphides

Advanced ceramics such as titanium carbide (TiC), molybdenum disulfide (MoS_2), and nickel phosphide (Ni_2P) provide high electrical conductivity, excellent chemical stability, and strong dielectric loss properties. Their unique electronic structures facilitate interfacial polarization and multiple scattering, making them highly effective absorbers across a broad frequency range. These materials are particularly suitable for aerospace and defense applications that demand thermal stability and corrosion resistance.

1.5.4.1. Limitations of Carbides, Sulphides, and Phosphides

- The synthesis process is associated with high costs and significant energy consumption.
- The limited flexibility of these devices makes them unsuitable for lightweight or wearable applications.
- The material is often brittle, making it challenging to work with when creating complex geometries.

1.5.5 High Entropy Materials

A novel class of microwave absorbers known as high entropy materials (HEMs) is created by mixing several primary elements in nearly equal proportions [35]. These materials, which include high entropy oxides (HEOs) and alloys (HEAs), have distinct microstructures with

numerous polarization centres and a high density of defects, which enhances electromagnetic wave attenuation. Their mechanical robustness, superior thermal stability, and adjustable electromagnetic characteristics make them attractive options for next-generation broadband microwave absorption applications [36].

1.5.5.1. Limitations of High Entropy Materials

- The synthesis is complex, and the processing costs are high.
- The current system lacks scalability for large-scale industrial applications.
- There is limited research data available on the long-term stability of the environment.

1.5.6 Biomass-Derived Materials

Biomass-derived microwave absorbers are eco-friendly, low-cost, and sustainable alternatives to conventional chemical-based materials. They are developed from agricultural wastes such as dried banana leaves (DBL), sugarcane bagasse (SG), coconut shells (CSH), and rice husks (RH), which are naturally rich in carbon content. These raw materials are capable of absorbing incident electromagnetic waves and converting them into heat energy. These materials are frequently mixed with conductive fillers like graphene or carbon nanotubes (CNTs) to improve their dielectric performance. These fillers greatly increase dielectric loss, conductivity, and impedance matching [37]. These composites are frequently utilized for a variety of applications due to their lightweight design, affordability, and powerful absorption capabilities. These include anechoic chambers for electromagnetic testing, radiation absorbent materials (RAMs) in stealth technology, antenna substrates for wireless communication systems, and EMI shielding in electronic devices.

1.5.6.1. Limitations of Biowaste Materials

- When used alone, it exhibits low electrical conductivity and poor dielectric properties.
- Narrow absorption bandwidth unless modified.
- Conductive additives are needed to improve performance.

1.5.7 Carbon-Based Materials

The high electrical conductivity, low weight, and potent dielectric loss characteristics of carbon-based microwave absorbers make them popular. High attenuation of electromagnetic waves is demonstrated by materials including carbon nanotubes (CNTs), graphene, carbon fibers, and activated carbon, which transform incident energy into heat through numerous scattering effects, polarization loss, and conduction loss. The porous structure of these materials promotes multiple reflections, further enhancing microwave attenuation. Their

broadband absorption and flexibility make them suitable for applications such as radar stealth technology and electromagnetic interference (EMI) shielding.

1.5.7.1. Limitations of Carbon-Based Materials

Despite their superior properties, pure carbon-based absorbers have some critical drawbacks

- High fabrication cost, especially for CNTs and graphene due to complex synthesis techniques.
- Agglomeration issues, as these nanomaterials tend to cluster, reducing uniform dispersion and performance.
- Mechanical limitations at high load can lead to decreased flexibility and reduced structural integrity.

Among all microwave absorber types (such as magnetic materials, 2D materials, metal oxides, carbides, and high-entropy materials), biomass-derived materials combined with carbon-based fillers have emerged as the most promising solution. Biomass materials like dried banana leaves (DBL), sugarcane bagasse (SG), rice husks, and coconut shells are eco-friendly, sustainable, lightweight, and low-cost, making them excellent candidates for green material development. However, their poor electrical conductivity limits their microwave absorption efficiency. However, despite their strong dielectric loss, multiple scattering effects, and excellent electrical conductivity, carbon-based materials such as graphene, carbon fibers, activated carbon, and carbon nanotubes (CNTs) are costly and challenging to process on their own for large-scale applications. The synergistic composite that is produced when biomass and carbon nanotubes are combined is economical, environmentally benign, and able to perform better in microwave absorption because of enhanced conductivity, dielectric loss, and impedance matching [39]. This composite approach is widely adopted in modern research for developing sustainable, high-performance microwave absorbers for EMI shielding, radar stealth technology, aerospace, and communication systems [40].

1.6 WHY CARBON NANOTUBES ARE THE BEST CHOICE

Carbon nanotubes (CNTs) are considered a significant advancement in nanotechnology because of their remarkable mechanical, electrical, and structural characteristics. As shown in Figure 1.10, these are cylindrical allotropes of carbon made by rolling one or more graphene sheets, a single layer of carbon atoms lined up in a two-dimensional honeycomb lattice, into seamless tubes [41,42]. These structures typically possess diameters in the nanometre range (approximately 0.4 to 100 nm) and can extend up to several micrometres in length. The carbon

atoms in CNTs exhibit sp^2 hybridization, which imparts exceptional structural integrity, as well as outstanding electrical and thermal properties.

An important turning point in materials science was reached in 1991 when Sumio Iijima discovered CNTs [43]. Due to their remarkable nanoscale size, extraordinarily high aspect ratios, and adjustable properties, carbon nanotubes (CNTs) have attracted significant research interest. Because of these qualities, carbon nanotubes (CNTs) are ideal for many kinds of applications, such as energy storage systems, structural composites, electronics, and materials that absorb microwave radiation [44].

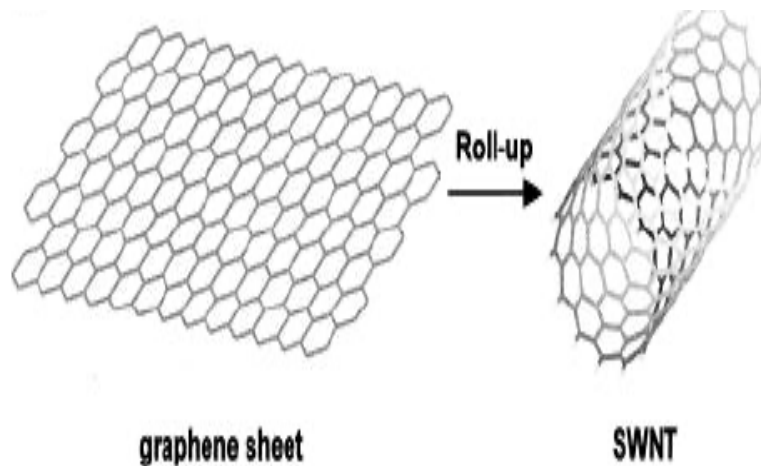


Figure 1.10 Formation of Carbon Nanotube (CNT) by Rolling a Graphene Sheet

1.6.1 Classification of Carbon Nanotube

The number of graphene layers that are rolled into cylindrical shapes determines the classification of CNTs. This classification significantly influences their properties, synthesis methods, and applications in various fields, including microwave absorption. SWCNTs (single-walled carbon nanotubes) and MWCNTs (multi-walled carbon nanotubes) are the two varieties of CNTs [45].

1.6.1.1 Single-walled carbon nanotubes (SWCNT)

In order to create SWCNTs, a single graphene sheet is rolled into a seamless cylindrical shape. Their chiralities, such as armchair, zigzag, or chiral, determine whether they behave in a metallic or semiconducting manner, as shown in Figure 1.11. Usually measuring between 0.7 and 2 nm in diameter and 0.5-5 μm in length, they have a very high aspect ratio [43]. SWCNTs possess outstanding properties, including high electrical conductivity, superior thermal conductivity comparable to diamond, and extraordinary mechanical strength resulting from sp^2

carbon bonding. These characteristics make SWCNTs highly suitable for advanced applications such as nanoelectronics, sensors, and high-performance composites. SWCNTs improve dielectric loss in microwave absorption because of their superior conductivity; nevertheless, their expensive cost of production and complicated processing prevent them from being widely used in absorber materials [46].

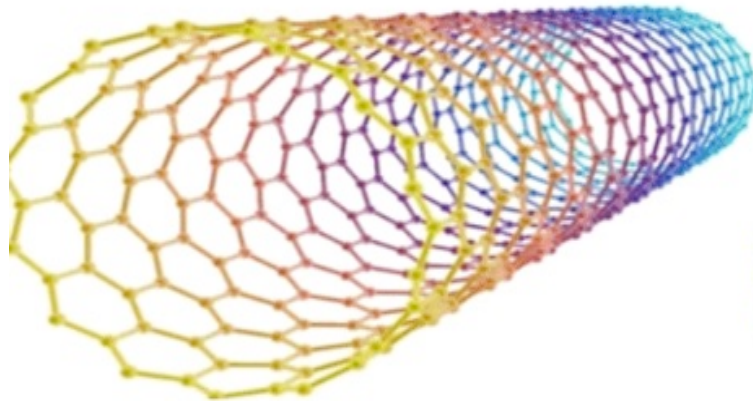


Figure 1.11 Single-walled Carbon nanotube structure[46]

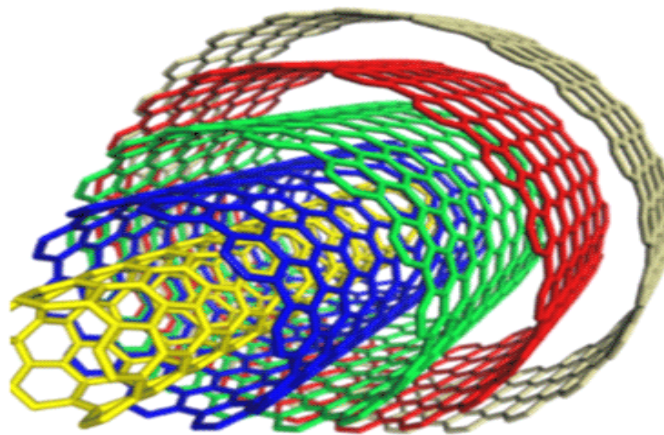


Figure 1.12 Multi-walled Carbon nanotube structure [46]

1.6.1.2 Multi-walled carbon nanotubes (MWCNTs)

MWCNTs are made up of several concentric graphene cylinders stacked in a tree-like pattern, with an interlayer spacing of roughly 0.34 nm , which is comparable to the spacing seen in graphite, as seen in Figure 1.12 [47]. Their diameters typically range from 2 to 100 nm , while their lengths can extend to 1 to $50\text{ }\mu\text{m}$, resulting in a very high aspect ratio. MWCNTs are appropriate for extensive industrial and research applications since they are somewhat simpler

15 to synthesize and more affordable than SWCNTs. They exhibit excellent mechanical strength, high thermal stability, and substantial electrical and thermal conductivity (though slightly lower than SWCNTs). Owing to these properties, MWCNTs are widely utilized in composites, EMI shielding, microwave absorbers, and structural reinforcement materials. For microwave absorption applications, MWCNTs are particularly preferred because they are economical, easy to disperse, and retain high electrical conductivity, which enhances dielectric loss, interfacial polarization, and impedance matching, thereby improving the overall absorption performance of the composite.

1.6.2 Properties of Carbon Nanotubes Relevant to Microwave Absorption

Carbon Nanotubes (CNTs) have a unique combination of physical, chemical, and structural properties that make them highly effective as reinforcing fillers in microwave absorbing materials (MAMs). These characteristics contribute to improved electromagnetic wave attenuation through various mechanisms, primarily dielectric loss and interfacial polarization. The key properties are outlined below:

1.6.2.1 High Electrical Conductivity

The delocalized π -electron cloud in CNTs gives them exceptional electrical conductivity due to their graphene-like structure. This high conductivity allows CNTs to serve as efficient pathways for the movement of electrons within a composite matrix. Conduction loss, a critical mechanism in dielectric microwave absorption, is significantly enhanced, which leads to improved energy dissipation of incident electromagnetic (EM) waves.

1.6.2.2 Large Specific Surface Area

CNTs have an exceptionally high surface-to-volume ratio owing to their nanoscale diameter and extended cylindrical shape. Strong interfacial interactions among CNTs and the underlying matrix material are made possible by their large surface area, which enhances interfacial polarization [48]. Such polarization plays a crucial role in converting EM energy into heat, thereby increasing absorption efficiency.

1.6.2.3 Strong Mechanical Strength

One of the most outstanding characteristics of CNTs is their extraordinary mechanical strength. CNTs possess a tensile strength nearly 100 times greater than steel, while maintaining only a fraction of its weight. This property ensures the fabrication of durable and mechanically robust absorber composites, which can withstand harsh environmental and operational conditions.

1.6.2.4 Lightweight and Low-Density

Despite their impressive mechanical performance, CNTs are extremely lightweight, making them an ideal candidate for applications where weight reduction is essential. This is particularly important in aerospace and defence sectors, where minimizing the overall weight of components without compromising performance is critical.

1.6.2.5 High Aspect Ratio

CNTs possess a precise high aspect ratio, often exceeding 1000, which enables the formation of percolative conductive networks even at low filler concentrations. These conductive networks enhance multiple loss mechanisms, such as multiple scattering of EM waves and extended conduction pathways, leading to better absorption performance across a broad frequency range.

1.6.2.6 Thermal Stability

CNTs exhibit excellent thermal stability and can tolerate extremely high temperatures without significant structural degradation. This characteristic indicates that CNT-based microwave absorbers will remain intact and functioning at high temperatures, which is essential for use in electronic devices, radar systems, and aircraft [49].

1.6.3 Influence of CNTs on Microwave Absorption

The distinct electrical, structural, and interfacial characteristics of CNTs contribute significantly to the enhancement of MAM performance [50]. The potential of CNTs to increase dielectric loss, encourage interfacial polarization, and enable multiple electromagnetic waves scattering accounts for their beneficial effects in this electromagnetic field. Below is a description of the influence of CNTs on microwave absorption [51]:

1.6.3.1 Enhancing Dielectric Loss

CNTs exhibit high electrical conductivity, which allows them to act as effective lossy materials. Conduction loss happens when electromagnetic (EM) waves encounter CNTs because free electrons migrate throughout the conductive network [52]. Additionally, CNTs contain surface defects and functional groups that contribute to dipolar polarization, further improving the dielectric loss mechanism. This enhanced dielectric loss is critical for converting incident EM energy into heat, thereby improving overall absorption.

1.6.3.2 Generating Interfacial Polarization

In CNT-based composites, the interface between CNTs and the other matrix material creates numerous heterogeneous boundaries. Under an electromagnetic field, the formation of charges at these surfaces causes Maxwell-Wagner polarization, also referred to as interfacial

polarization [53]. This phenomenon contributes significantly to dielectric relaxation, increasing the attenuation of EM waves.

1.6.3.3 Increasing Multiple Scattering

Multiple internal reflections and EM wave scattering are supported within the composite material by the high aspect ratio and network-like structure of CNTs. Absorption efficiency is improved throughout a wide frequency range because of the prolonged EM wave propagation path inside the absorber, which causes more energy to be dissipated before the waves can exit.

1.6.3.4 Improving Impedance Matching

The absorber material's impedance should be near that of free space in order to reduce reflection at the air-material contact and enable efficient microwave absorption [54]. CNTs, when incorporated into a dielectric or magnetic matrix, help in tuning the complex permittivity of the composite, which improves impedance matching. This improves absorption performance by allowing more incoming electromagnetic energy to pass through the absorber rather than being reflected.

1.6.3.5 Forming Synergistic Composites

Hybrid composites can be created by combining CNTs with biowaste-derived materials like rice husk, sugarcane bagasse, or coconut husk [55]. This combination influences the complementary properties of both components: CNTs contribute high electrical conductivity and dielectric loss, while biowaste materials provide a lightweight structure and cost-effectiveness. Since the composite attenuates EM waves via a variety of mechanisms, including conduction loss, interfacial polarization, and multiple scattering, the ensuing combination permits broadband microwave absorption [56]. These environmentally friendly hybrid systems are especially useful for applications that require wide frequency coverage, like EMI shielding, RCS reduction, and stealth technology [57].

CNTs are highly effective at increasing microwave absorption because of their large surface area, high aspect ratio, and superior electrical conductivity, which enhance mechanisms such as dielectric loss, interfacial polarization, and multiple scattering [58]. These properties make CNTs ideal for lightweight, thermally stable, and mechanically strong absorbers in aerospace, defence, and stealth applications. MWCNTs are especially favoured because they are less expensive and simpler to produce than SWCNTs, while still offering notable enhancements in impedance matching and dielectric characteristics.

When combined with biomass-based materials, CNTs greatly enhance electromagnetic attenuation by improving conductivity and polarization, even at very low filler content. This hybrid approach overcomes the natural limitations of biomass (such as low conductivity) while avoiding the high cost and weight of pure carbon absorbers. The result is an eco-friendly, cost-effective, and high-performance composite that meets the demands of next-generation EMI control, stealth technology, aerospace systems, and wireless communication applications.

1.7 MOTIVATION

The development of high-frequency electronic equipment, radar, and contemporary wireless communication systems has resulted in a notable rise in EM wave emissions. This has led to significant electromagnetic pollution and EMI, which have a negative effect on the functionality and dependability of delicate electronic devices and could be harmful to human health. Thus, creating effective MAMs has emerged as a crucial field of study for EMI mitigation and guaranteeing electromagnetic compatibility (EMC) in a range of applications, such as consumer electronics, automotive, aerospace, and defence [59].

Conventional microwave absorbers, such as ferrite-based and chemical-based composites, although effective, suffer from drawbacks such as high density, limited bandwidth, brittleness, and environmental hazards. Moreover, the rising demand for lightweight, cost-effective, broadband absorbers with thermal stability has necessitated the exploration of alternative materials. In recent years, attention has shifted towards sustainable and eco-friendly solutions utilizing agricultural waste as a base material due to its abundance, biodegradability, and low cost. Among various agricultural wastes, DBL and SG have emerged as promising candidates due to their porous structure and carbon content, which can contribute to dielectric loss when properly processed. However, agricultural waste alone exhibits low conductivity, resulting in limited microwave absorption performance. To overcome this limitation, hybrid composites incorporating conductive nanomaterials such as MWCNTs were introduced [60]. MWCNTs exhibit excellent electrical conductivity, high aspect ratio, and strong dielectric properties, significantly enhancing microwave absorption through polarization and conduction loss mechanisms.

Despite significant progress in MWCNT-based composites, most studies focus on synthetic polymer matrices, which are neither eco-friendly nor cost-effective. Very limited research has been reported on optimizing bio-based composites with MWCNTs for X-band frequency

applications. Furthermore, for such sustainable systems, the impact of filler loading and composite thickness on reflection loss (RL) performance has not been well examined.

This thesis is driven by the need to create MAMs that are lightweight, inexpensive, and environmentally friendly by combining agricultural waste with a small quantity of carbon nanotubes (CNTs) to achieve high performance while addressing environmental concerns. By fabricating and analyzing DBL-MWCNT and SG-MWCNT composites, the purpose of this study is to assess their microwave absorption and dielectric characteristics throughout the X-band, along with determining the ideal thickness and filler content for maximum absorption. The findings of this research will not only contribute to EMI mitigation but also promote the utilization of agricultural residues, thereby supporting sustainable development.

1.8 THESIS CONTRIBUTIONS

This thesis focuses on the development and performance evaluation of eco-friendly microwave absorber materials derived from agricultural waste combined with carbon nanotubes (CNTs). The primary objective is to optimize the absorption characteristics of these composite materials under various environmental conditions, particularly thermal variations. The contributions of this thesis are summarized as follows:

- First objective is to study and analysis of magnetic and dielectric properties of different types of agriculture waste and Carbon nanotubes materials as microwave absorbers.

In this objective, an initial in-depth investigation of the underlying principles of microwave absorption is carried out to understand the mechanisms responsible for energy attenuation, such as dielectric loss and magnetic loss. After this theoretical understanding, the dielectric and magnetic properties of agricultural waste-based materials are analyzed within the X-band frequency range (8.2–12.4 GHz). The selected agricultural wastes include teak wood sawdust (TWSD), dried banana leaves (DBL), and sugarcane bagasse (SG) due to their natural abundance, cost-effectiveness, and environmental benefits. Their dielectric behaviour is evaluated to determine their suitability as microwave absorbers. After completing this analysis, the dielectric properties of carbon nanotubes (CNTs) are studied to understand their contribution and effectiveness as a microwave absorbing material.

- The second objective is to develop dried banana leaves/CNT and sugarcane bagasse/CNT-based composite materials and investigate their microwave absorption properties.

In this objective, Composite samples are fabricated by blending optimized ratios of agricultural waste powders with multi-walled carbon nanotubes (MWCNTs). Performance evaluation of these composites is carried out by analyzing dielectric properties, reflection loss, bandwidth, and absorption efficiency. Structural and morphological characterizations are also performed to understand material behaviour.

- The third objective is to examine the impact of thermal-aware environmental conditions on the developed composite materials and analyze their microwave absorbing properties.

In this objective, Temperature variation effects on the microwave absorption properties of the dried banana leaves and dried banana leaves with multiwalled carbon nanotubes composites are studied to assess thermal stability. The reflection loss performance at different temperatures is evaluated to determine the reliability of these materials under real-time thermal conditions. The results demonstrate that the developed composite maintains stable microwave absorption performance across varying thermal environments.

1.9 THESIS ORGANIZATION

Chapter 1 introduces microwave absorber materials (MAMs), their working principles, importance in mitigating electromagnetic pollution, and classification. It also presents a brief overview of carbon nanotubes (CNTs), their properties, classification, and their role in improving microwave absorption. The importance of biowaste-based MAMs for cost-effectiveness and eco-friendliness is also highlighted. Finally, the thesis organization is described.

Chapter 2 provides a comprehensive literature review of microwave absorber materials. It discusses chemical-based absorbers, their performance, and drawbacks such as toxicity and environmental hazards. It also reviews biowaste-based absorbers, their composites with conductive fillers (like CNTs), and factors influencing absorption performance. Research gaps, particularly regarding biowaste-CNT composites under thermal conditions, are identified. Based on these gaps, the research objectives of the thesis are formulated.

Chapter 3 presents an overview of microwave absorption properties of agricultural waste and CNTs. It explains the fundamental dielectric and magnetic properties of absorber materials, mechanisms responsible for microwave absorption, and experimental evaluation of agricultural wastes (DBL, SG, TWSD) in the X-band frequency range. The role of CNTs in enhancing dielectric and absorption performance is also highlighted.

Chapter 4 describes the development of dried banana leaves (DBL)/CNT-based composites. It explains the fabrication process, structural and elemental characterization, and microwave absorption performance analysis across different thicknesses and filler contents. The results are correlated with theoretical models to understand dielectric behaviour and absorption mechanisms.

Chapter 5 focuses on the development of sugarcane bagasse (SG)/CNT-based composites. The fabrication, dielectric characterization, and microwave absorption studies in the X-band are presented. The influence of CNT loading and composite thickness on absorption performance is analyzed in detail.

Chapter 6 investigates the impact of thermal variations on the microwave absorption properties of biowaste-based absorbers. Specifically, the performance of DB and DB-CNT composites is studied under different temperatures in the C-band frequency range. The role of CNTs in enhancing thermal stability and maintaining reliable absorption performance is evaluated.

Chapter 7 concludes the thesis by summarizing the findings and highlighting the significant contributions of the research. The chapter also outlines possible future directions for the development of sustainable, cost-effective, and high-performance microwave absorber materials.

CHAPTER 2

LITERATURE REVIEW

This chapter provides a comprehensive review of the existing literature on MAMs and their role in minimizing electromagnetic interference. The discussion starts with research on chemical-based absorbers, emphasizing their excellent performance characteristics along with challenges such as environmental hazards, toxicity, and high manufacturing costs. Next, the review highlights biowaste-based absorbers, which have attracted interest as eco-friendly and cost-effective alternatives. These absorbers are notable for their abundance, biodegradability, and high carbon content. These materials come from agricultural residues like rice husk, coconut husk, corn husk, and banana leaves, providing sustainable solutions for microwave absorption applications.

Further, the chapter discusses biowaste composite absorbers that integrate agricultural waste with conductive materials, including charcoal, coal, carbon nanotubes (CNTs), and ferrites. These hybrid composites are engineered to address the limitations of raw biomass, especially its low electrical conductivity, by enhancing dielectric properties and achieving a broader absorption bandwidth. Key factors such as filler loading, thickness optimization, and structural characteristics that influence electromagnetic wave attenuation are discussed in detail.

While some studies have explored the thermal stability and temperature-dependent behaviour of chemical-based MAMs, research on biowaste composite absorbers under thermal conditions is still limited. Evaluating these properties is crucial for real-world applications in aerospace, defence, and electronic systems, where temperature variations can significantly affect absorber performance.

This chapter presents a detailed review of previous research on microwave absorber materials, organized into three main sections:

- **Chemical-Based Microwave Absorber Materials** - Overview of conventional synthetic absorbers and their limitations.
- **Biowaste-Based Microwave Absorber Materials** - Studies on absorbers derived from agricultural and organic waste.
- **Biowaste Composite-Based Microwave Absorbers** - Studies on composites combining biowaste with nanomaterials for enhanced absorption.

2.1 CHEMICAL-BASED MICROWAVE ABSORBER

The constant development of advanced electronic devices, radar technologies, wireless communication networks, and stealth applications has led to a notable rise in EMI [61]. EMI adversely affects the performance of sensitive electronic devices, leading to signal distortion, data loss, and malfunctioning of systems. To overcome these issues, researchers developed MAMs, which reduce EMI and provide uninterrupted device operation by reducing incident electromagnetic waves by transforming them into thermal energy [62].

Initially, researchers focused on developing conventional microwave absorbers from chemical-based materials, as these materials could provide high dielectric and magnetic losses, essential for effective EMI suppression. These chemical-based absorbers include ferrites, conductive polymers, and synthetic carbon-based materials, each utilizing different absorption mechanisms such as magnetic resonance, dielectric polarization, and multiple reflection effects.

M.Amano et al. [63] examined a novel method of adding perforations (multiholes) to the absorber structure to improve the efficiency of ferrite-based microwave absorbers. Their research, which was backed by both confirmation from experiments and finite-difference time-domain modelling, showed that making tiny holes in a ferrite layer can greatly increase the matching frequency band from 1 GHz to over 4 GHz while lowering the thickness requirements. Their research, which was backed by both confirmation from experiments and finite-difference time-domain modelling, showed that making tiny holes in a ferrite layer can greatly increase the matching frequency band from 1 GHz to over 4 GHz while lowering the thickness requirements. The proposed design achieved a thin absorber of 3.0 mm at 2.45 GHz by applying a double-layer structure composed of rubber ferrite and carbonyl iron, which provides high imaginary permeability essential for effective absorption. Design charts for various parameters, including hole diameter and spacing, were presented to optimize performance for normal incidence conditions. Additionally, the idea was effectively expanded to produce a 1.6 mm thickness absorber at 5.8 GHz having an RL of -20 dB, demonstrating how well structural changes can enhance broadband absorption properties.

Y.B. Feng et al. [64] presented that rubber-based radar absorbing materials (RAMs) were developed using carbonyl iron and barium ferrite ($\text{BaZn}_{1.5}\text{Co}_{0.5}\text{Fe}_{16}\text{O}_{27}$) powders as primary microwave absorbers. In the 2-18 GHz band, the research examined complex permittivity and permeability of absorbers using various powder compositions, building a database for effective

absorber design. After designing and analyzing both single-layer and double-layer absorbers, it was determined that the former had a wider absorption bandwidth than the latter. The double-layer design demonstrated remarkable effectiveness for military camouflage and EMI suppression. It features a compact thickness of 3.6–3.7 mm and achieves a reflection loss (RL) of less than -13 dB between 6–8 GHz, as well as less than -8 dB across a frequency range of 2–18 GHz. The morphological examination showed that the barium ferrite powder had a W-type hexagonal flake structure, which helped to improve the absorption performance, but the carbonyl iron powder, which was made by thermally breaking down iron pentacarbonyl, had a spherical cubic structure.

V. Sunny et al. [65] revealed how pre-characterized nickel ferrite (NiFeO_4) nanoparticles were mixed into a natural rubber matrix to create flexible magnetic composite materials. Using the cavity perturbation technique, the complex dielectric permittivity and magnetic permeability of these combinations were determined at different microwave frequencies. With increasing filler concentration, the study found that dielectric permittivity improved gradually. This was well predicted using Maxwell-Garnett mixture equations. Utilizing the single-layer absorber model supported by a perfect conductor, the microwave absorption performance was examined. The composites showed an RL of -5.9 dB at 3.2 GHz for a 12 mm thickness in the S-band and an RL of -16 dB at 9.5 GHz in the X-band. These findings indicate that rubber-ferrite nanocomposites are lightweight, flexible, and mechanically stable, making them suitable for microwave absorption applications.

S.B. Narang et al. [66] examined Co-Ti substituted barium ferrites with the standard formula $\text{BaFe}_{(12-2x)}\text{Co}_x\text{Ti}_x\text{O}_{19}$ ($x = 0.0, 0.3, 0.5, 0.7, 0.9$) for their microwave absorption characteristics. In the X-band frequency range, the study used X-ray diffraction (XRD), scanning electron microscopy (SEM), vibrating sample magnetometer (VSM), and vector network analyzer (VNA) to examine the structure, morphology, magnetic properties, and microwave absorption. The findings showed that reducing particle size, decreasing resistance, and increasing dielectric loss greatly improve microwave absorption. The optimal performance was observed for $x = 0.7$, which exhibited 99% absorption with a peak of RL -25.15 dB at a 3.3 mm thickness. According to the results, Co-Ti substitution in barium ferrite successfully adjusts coercivity and dielectric losses, which makes matrices with $x = 0.5$ and $x = 0.7$ attractive options for effective X-band microwave absorbers.

L. Wang et al. [67] examined the fabrication of composites of ferrite, Co, and porous carbon made by thermally carbonizing ferrite and ZIF-67 in situ in a nitrogen atmosphere. These composites exhibited a magnetoelectric synergistic effect, enhancing their microwave absorption properties through mechanisms such as impedance matching, interface polarization, multiple reflections, and scattering losses. The study made clear how important the carbonization temperature is to retaining the porous structure, as excessive heat leads to structural collapse. FC500 (carbonized at 500 °C) achieved a maximum RL of -31.05 dB at 14.32 GHz with a 4.8 GHz EAB (Ku band, 1.5 mm). At 2.5 mm, it showed an RL of -47.31 dB at 8.4 GHz with a 2.72 GHz EAB (6.80-9.52 GHz). These effects indicate that ferrite/Co/porous carbon composites not only deliver broad bandwidth and strong absorption but also significantly reduce weight due to their thin optimal thickness and high specific surface area (69.3 m²/g⁻¹), making them promising candidates for lightweight, high-performance microwave absorbers.

T. Indrusiak et al. [68] studied the microwave absorption of ferrite-epoxy composites using Ni_{0.5}Zn_{0.5}Fe₂O₄, NiFe₂O₄, and Fe₃O₄ nanoparticles (20 and 40 wt%). SEM and TEM confirmed fractal filler structures with rough surfaces. Electromagnetic properties of 1 mm monolayers in the X-band showed Ni_{0.5}Zn_{0.5}Fe₂O₄ composites with superior RL. Multilayer designs with low-dielectric spacers (air, honeycomb, foam) enhanced impedance matching. The best structure, ER/NiZn(40)-honeycomb-ER/NiZn(20), achieved -39.83 dB at 8.75 GHz (99.99% absorption), while ER/NiZn(20)-foam-ER/NiZn(40) reached -24.15 dB at 9.12 GHz. With only 6 mm thickness, these multilayers provide lightweight absorbers for civil and defence use.

H. Yang et al. [69] developed graphene/BaFe₁₂O₁₉-CaFe₂O₄-CoFe₂O₄ ferrite composites via deoxidation to improve microwave absorption. Characterization confirmed enhanced properties, with the best sample showing an RL of -36.8 dB at 9.9 GHz (2.9 mm). The improvement was linked to combined dielectric-magnetic losses and better impedance matching, highlighting the promise of multi-component ferrite-graphene systems for advanced absorbers.

Y. Liu et al. [70] created CoOx/carbon fiber composites by thermally oxidizing them at 350 °C after electroless cobalt plating. Ferromagnetic behaviour was observed in the resultant Co₃O₄/CoO layers (~0.7 µm), with H_c = 464.8 Oe, M_s = 10.62 emu/g, and M_r = 2.21 emu/g. Microwave studies revealed that the RL was -45.16 dB at 13.41 GHz (1.5 mm), RL was -10 dB from 4.04-18.00 GHz, and RL was -20 dB from 11.54-14.77 GHz. These composites are

excellent prospects for cutting-edge microwave absorbers because they exhibit broadband, high-efficiency absorption at thin thicknesses.

J. Liu et al. [71] synthesized Fe nanowires (70–200 nm diameter, 20–50 μm length) using a chemical vapor deposition (CVD) method for EM wave absorption applications. The frequency-dependent relative ϵ_r and μ_r were significantly influenced by nanowire diameter. Due to less eddy current loss, the nanowires showed a magnetic resonance peak (μ_r'') between 1 and 18 GHz, in contrast to micrometre-sized wires or flake-like samples. Resin compacts with 29 vol% Fe nanowires (1.3–4.0 mm) showed effective absorption across 5.6–18 GHz, highlighting their promise for broadband microwave applications.

J. Li et al. [72] examined Co nanoplatelets that are present at room temperature in both the fcc and hcp phases (diameter: 120 nm, thickness: 10 nm). Because of an oxide layer, the saturation magnetization was lower than that of bulk Co, but the coercivity was higher. Without an external field, each nanoplatelet had a vortex magnetic structure. To enhance electromagnetic properties, the nanoplatelets were coated with MnO_2 and mixed with paraffin wax. Microwave measurements in the 0.1–18 GHz range revealed two broad, significant peaks in complex permeability and one in complex permittivity. Numerical simulations indicated that MnO_2 -coated Co nanoplatelet composites achieved reflection loss below -12 dB in 2–11.5 GHz range, suggesting their potential as effective microwave absorbers.

B. Zhang et al. [73] investigated flake-like Alnico powder as a thin S-band absorber. Produced via single-roller melt-spinning, Alnico/paraffin composites showed peak permittivity and permeability at 2 GHz. A composite with 60% Alnico and 1.8 mm thickness achieved an RL of -11.4 dB. Adjusting thickness and filler content-controlled absorption, while high saturation magnetization and low initial permeability enabled higher resonant frequencies (1.4 GHz), making these composites suitable as lightweight, thin S-band absorbers.

J.R. Liu et al. [74] studied nanocomposites made by mechanically alloying α -Fe with rare-earth powders, examining their magnetic and microwave absorption properties. Saturation magnetization increased with α -Fe content, while coercivity was higher than pure α -Fe due to shape anisotropy and exchange bias. Resin compacts (33.5 vol% rare-earth with 38–85 vol% α -Fe) showed effective absorption across 4.3–16.0 GHz at thicknesses of 1.3–3.2 mm, highlighting α -Fe nanocomposites as lightweight, efficient microwave absorbers.

Y.Q. Kang et al. [75] prepared BiFeO_3 (BFO) nanoparticles (60–120 nm) via sol-gel and studied their Ku-band microwave absorption. RL exceeded 10 dB (90% absorption) from 13.1–

18 GHz, with a maximum of -26 dB at 16.3 GHz. Enhanced performance was due to combined ferroelectric and weak ferromagnetic order, effective impedance matching, and nanoscale confinement, making BFO nanoparticles promising microwave absorbers.

J.R. Liu et al. [76] reported the synthesis of α -Fe/Y₂O₃ nanocomposites using the melt-spinning technique and evaluated their microwave absorption performance. The nanocomposites exhibited strong absorption properties, achieving RL values below -20 dB in the 2.0-3.5 GHz frequency range for absorber thicknesses between 3 and 5 mm. The maximum RL of -36 dB occurred at 2.6 GHz with a 4 mm thickness. These results indicate that α -Fe/Y₂O₃ nanocomposites are promising for S-band microwave absorption applications.

X.G. Liu et al. [77] studied FCC-Co/Al₂O₃ and FCC-Co/Y₂O₃ nanocapsules made via modified arc-discharge. Both showed a magnetic resonance peak at 6.4 GHz. FCC-Co/Al₂O₃ achieved RL < -20 dB from 9.6-11 GHz at 4-5 mm thickness with a minimum RL of -29.7 dB at 10 GHz. FCC-Co/Y₂O₃ exhibited a broader RL < -20 dB range (9.7-12.4 GHz) at thinner thicknesses (2-4 mm) due to higher magnetization. Enhanced absorption results from good impedance matching, strong natural resonance, and interfacial polarization, making these nanocapsules suitable for X-band applications.

X. Qi et al. [78] synthesized carbon nanostructures-CNFs, bamboo-like CNTs, and CNSs-via acetylene pyrolysis at 500–700 °C using Fe/SnO₂ nanoparticles from sol-gel and hydrogen reduction. The method, which avoids dilute gases, is environmentally friendly. Pyrolysis temperature strongly affected yield, morphology, and microwave absorption, with maximum yields of 25.595%, 36.791%, and 37.039% for CNFs, CNTs, and CNSs, respectively. These carbon nanostructures showed excellent microwave absorption, demonstrating potential for EM wave absorption applications, and a formation mechanism was proposed.

Y. Yang et al. [79] created iron-coated carbon fibers using electrochemical techniques and investigated their magnetic, permeability, and permittivity characteristics. They were appropriate for microwave absorption due to their low coercivity. When added in small amounts to standard absorbers like carbonyl iron, they significantly increased permittivity and permeability without raising filler density, enabling thinner absorption layers and improved performance.

Y.H. Fang et al. [80] investigated a Ni-coated single-walled carbon nanotube (NiCo-SWCNT) and CoFeO₄ nanocomposite that absorbs microwaves. Sol-gel (CoFeO₄) and direct current arc discharge (NiCo-SWCNTs) techniques were used to create the materials. Properties of

microwave and electromagnetic absorption were assessed in the 2–18 *GHz* range. At 14.7 *GHz*, a composite with 15 wt.% NiCo-SWCNTs demonstrated the best performance, with a reflection loss of -47.9 dB. At a corresponding thickness of 1.8 mm, the absorption bandwidth (RL < -1 dB) covered 7.1 *GHz* (10.5-17.6 *GHz*). According to the study, this nanocomposite shows promise as a lightweight microwave absorber.

X. Zhang, G. Zhang, G. *et al.* [81] discussed a double-layer cementitious material composed of Mn-Zn Ferrite material and chemical materials, which was used as a microwave absorber material. It shows that in addition to fume silica, it could recover impedance matching between cementitious Composite material and free space. If cement-based absorber material was used as a mortar impedance matching layer with silica fume to adjust the permeability of the surface material. They found that the microwave reflection of ferrite-filled double-layer mortars due to the impedance was more than that of plain mortar. Compared the double layer structure with a single layer structure, and the excellent impedance property is due to matching the impedance of the material. Double-layer plate access to 12.04 *GHz* frequency range - 15 dB reflection loss

S. Iijima [82] reported on carbon nanotubes (CNTs), highlighting that their structure, formed from rolled graphite sheets, gives them exceptional properties. CNTs are classified as single-walled (SWCNTs) and multi-walled (MWCNTs), both exhibiting remarkable electrical, mechanical, chemical, and electronic characteristics, making them useful across diverse scientific, engineering, and technological applications.

X. Zhang, S. Zhaou, *et al.* [83] examined the ability of MWCNTs, which were built on reinforced cement composite, to absorb waves.. They developed an MWCNT and Portland cement composite and evaluated their electromagnetic wave absorbing property. Sample thickness and MWCNT content effects were observed in the 2-18 *GHz*. The absorbing properties were achieved by a cement-based composite, and the content of MWCNT also depends on the thickness of the sample. They used MWCNT contents of 0.25, 0.50, 0.75, and 1.00% and the thickness of the sample was 5mm; it was unstable due to the resonance absorption. If the sample thickness was increased to 10mm and 15mm, then it gave the best stable microwave absorbing properties. Also showed that the sample with 15 mm thickness had a better absorbing property than the 10 mm sample. If the CNT content of 0.50 % with a sample thickness of 5mm, it gave the best absorbing property, and the RL was -15.3dB.

C. Huo *et al.* [84] designed the double-layer polymer composite, which could improve the absorption properties of the overall EM wave. The rare metal doping enhanced the ability of

MWCNTs to absorb electromagnetic waves. The polymer matrix in its paper was discussed in the form of an absorber in the first and second layers, the mixed multi-walled carbon nanotube with various rare metals, and pure MWCNT. This composite gives -10dB reflection loss on the overall 2-18 GHz frequency range.

Table 2.1 presents a summary of the microwave absorption performance of various chemical-based MAMs, highlighting their frequency range, thickness, and minimum RL.

Table 2.1 Microwave Attenuation Properties of Chemical-Based Absorber Materials

S.no	Absorber	Frequency (GHz)	Thickness d_m (mm)	RL (dB)	References
1	Fe	1-4	3	-20	[63]
2	BaZn _{1.5} Co _{0.5} Fe ₁₆ O ₂₇)	2-18	3.6-3.7	-13	[64]
3	NiFe ₂ O ₄	9.5	12	-16	[65]
4	Co-Ti	8.2-12.4	3.3	-25.15	[66]
5	ferrite/Co/porous	12.24-17.04	1.5	-31.05	[67]
6	ER/NiZn(40	8.2-12.4	-	-39.83	[68]
7	graphene/(1-x)BaFe ₁₂ O ₁₉ /CaFe ₂ O ₄ /xCoFe ₂ O ₄	9.9	2.9	-36.8	[69]
8	(CoOx/CFs)	11.54-14.77	1.5	-45.16	[70]
9	Fe nanowires	5.6-18	1.3-4	-47	[71]
10	Co nanoplatelets	2-11.5	1-4	-12	[72]
11	Alnico powder	3.7-5.5	1.2-1.8	-14	[73]
12	Z-type Ba-ferrite	4.6-12.4	2.8-5.4	-52	[74]
13	BiFeO ₃ nanoparticles	13.1-18	3.5	-26	[75]
14	α -Fe/Y ₂ O ₃	2-3.5	3-5	-36	[76]
15	Fcc-Co/Al ₂ O ₃	9.7-12.4	2-4	-21.4	[77]
16	Bamboo-like CNTs	12.4	1-2.5	-11.06	[78]
17	Fe ₃ O ₄ /Cf	3.52-10.01	2.9-5.12	-35	[78]
18	NiCo-SWCNT	12-18	1.8	-47.9	[80]
19	Mn-Zn Ferrite	8.2-12.4	-	-15	[81]
20	MWCNT and Portland cement composite	2-18	5	-15.3	[83]
21	Polymer-MWCNT	2-18	-	-10	[84]

91 It is clear that materials based on carbon and ferrite have remarkable microwave absorption capabilities. For example, Co–Ti substituted ferrites attained an RL of -25.15 dB within the X-Band at a thickness of 3.3 mm. In contrast, graphene/BaFe₁₂O₁₉/CaFe₂O₄/CoFe₂O₄ composites demonstrated even better absorption, with an RL of -36.8 dB at 9.9 GHz and a thickness of 11 only 2.9 mm. Furthermore, CoOx/CF composites confirmed remarkable performance, achieving RL of -45.16 dB in the frequency range of 11.54-14.77 GHz. Additionally, nanostructured materials such as Fe nanowires (RL = -47 dB), NiCo-SWCNT composites (RL = -47.9 dB), and α -Fe/Y₂O₃ nanocomposites (RL = -36 dB) showed outstanding performance. This is attributed to their high surface area and effective mechanisms for dielectric and magnetic loss. Moreover, Broadband absorption was achieved in certain composites, such as ER/NiZn ferrite with an RL of -39.83 dB and Z-type Ba-ferrite with an RL of -52 dB, making them very appropriate for X-band applications. Similarly, carbon-based microwave absorbers, including MWCNT/polymer composites and bamboo-like CNTs, demonstrated effective absorption even in thin layers, which is advantageous for lightweight applications. The literature review on chemical-based materials shows that they possess outstanding microwave absorption characteristics, with reflection loss values as low as -52 dB across wide frequency ranges. However, their large-scale use is limited by several factors, including the requirement for precise synthesis techniques, the use of costly raw materials, and environmentally harmful processing methods.

2.1.1 CHALLENGES RELATED TO FABRICATED CHEMICAL-BASED MAMs

15 Despite their excellent Microwave wave absorption properties, chemical-based MAMs face several challenges that restrict their large-scale and sustainable use. The major limitations include:

2.1.1.1 High Production Cost

130 Chemical-based MAMs provide excellent electromagnetic wave attenuation, but their large-scale use is limited due to high production costs. The limitation primarily stems from the use of expensive precursors, including transition metal oxides, ferrites, and carbon-based nanostructures. The synthesis of advanced nanostructured composites, such as carbon nanotubes (CNTs) and graphene, necessitates the use of costly catalysts like iron (Fe), cobalt (Co), or nickel (Ni) nanoparticles. Additionally, controlled fabrication environments, such as high-temperature furnaces or chemical vapor deposition (CVD) systems, are essential to ensure purity and maintain structural integrity. Additionally, post-processing steps such as

functionalization and dispersion contribute to higher manufacturing costs. **X.Qi et al.** [85] reported that the production of CNT-based absorbers involves expensive catalysts and precise pyrolysis conditions, which significantly add to the fabrication cost. Similarly, **Y.Yang et al.** [86] highlighted that the inclusion of iron-coated carbon fibers in composite absorbers enhances absorption properties but demands additional fabrication steps, thereby increasing overall production expenses.

2.1.1.2 Complex Fabrication Processes

The development of chemical-based MAMs typically requires advanced synthesis techniques such as sol-gel processing, hydrothermal synthesis, and electrochemical deposition to attain the required microstructure and electromagnetic properties. It takes a lot of time and effort to use these methods, and in order to guarantee uniformity and phase purity, variables like temperature, pH, and reaction duration must be strictly controlled. Additionally, post-treatment processes like calcination, sintering, and surface functionalization contribute to the complexity and extend processing time. **Y. Yang et al.** [86] highlighted that the electrochemical coating of carbon fibres with magnetic layers, while effective for enhancing absorption performance, adds multiple fabrication stages that complicate large-scale production.

X. Liu et al. [87] reported that the sol-gel and hydrothermal methods for preparing ferrite-based MAMs require extended reaction times and high-temperature annealing to achieve the necessary crystalline structure, making the entire process laborious and resource-intensive.

2.1.1.3 Bulkiness and High Thickness Requirement

The need for relatively large thicknesses to attain maximum absorption performance is one of the major drawbacks of chemical-based MAMs. Many ferrite-based and composite absorbers show strong reflection loss (RL) values only at thicknesses between 3 mm and 5 mm. This requirement increases the overall weight and bulkiness of the device. Such thickness values are not suitable for modern lightweight and compact applications, especially in industries where weight and space constraints are crucial, such as aviation, automobiles, and portable electronics. For instance, **J.R. Liu et al.** [76] reported that α -Fe/Y₂O₃ nanocomposites exhibited excellent microwave absorption characteristics, primarily due to their strong magnetic and dielectric losses. However, these composites achieved significant attenuation only when fabricated at a thickness of 3-5 mm, which is considerably large for practical applications requiring lightweight and compact designs. The increased thickness of the material directly impacts its usability in modern engineering sectors, such as aerospace and automotive

industries, where minimizing weight is crucial. This demand for greater thickness also raises material costs and complicates fabrication. Maintaining structural integrity with thicker layers often requires additional processing steps and stronger binders.

Similarly, **J.R.Zhao et al.** [74] observed that Ba-ferrite-based composites, despite their strong reflection loss (RL) and broad frequency absorption characteristics, demanded a minimum thickness of 2.8 mm or more to achieve optimal performance. This limitation restricts the use of these materials in thin coatings for stealth technology, electronic device shielding, and lightweight communication systems, where a thickness of less than 2 mm is typically preferred. While these materials exhibit excellent absorption efficiency, their reliance on substantial thickness for effective performance remains a significant drawback. This challenge has prompted researchers to seek out alternative absorbers that offer high attenuation capabilities while maintaining reduced thickness.

2.1.1.4 Environmental Concerns

The synthesis of MAMs that are chemical-based often relies on hazardous chemicals and energy-intensive processes, which present significant environmental and safety challenges. Sol-gel processing, CVD, and wet chemical synthesis are examples of advanced production techniques that demand significant quantities of strong acids, bases, and organic solvents.. This leads to the generation of toxic by-products and chemical waste during processing and post-treatment. If these by-products are not properly managed, they can contaminate soil and water, resulting in long-term ecological damage. The high energy consumption associated with processes like CVD, which operate at elevated temperatures in controlled atmospheres, contributes significantly to the overall carbon footprint of these materials, thereby reducing their sustainability. Additionally, many nanostructured materials, such as CNTs, require surface functionalization with strong oxidizing agents like nitric acid or sulfuric acid to enhance dispersion and compatibility. This further increases their environmental impact.

Y. Yang et al. [86] reported that the production of iron-coated carbon fibres involves several wet chemical processes. This not only complicates the manufacturing process but also generates a significant amount of chemical waste. These environmental concerns represent a major drawback of chemical-based materials and manufacturing (MAMs), especially when considering large-scale production, where waste management and energy requirements become even more critical. This circumstance emphasizes the critical need for sustainable,

environmentally friendly substitutes, like MAMs made from biowaste, which can significantly cut down on chemical use and lessen environmental risks.

2.1.1.5 Limited Temperature Stability

Chemical-based MAMs often have limited thermal stability, which restricts their use in high-temperature or harsh environmental conditions. Many ferrite-based absorbers and polymer composites can experience structural degradation or phase transitions at elevated temperatures, resulting in a decline in microwave absorption performance. For example, ferrites may lose magnetization due to thermal demagnetization, while polymer-based composites can soften or degrade when exposed to temperatures exceeding their glass transition or decomposition points.

H. Yang et al.[69] found that Ba-ferrite-based absorbers, although they exhibit excellent absorption performance at room temperature, experience a decrease in reflection loss when subjected to higher temperatures. This reduction is mainly due to the degradation of their magnetic properties. Similarly, **X. Qi et al.** [85] pointed out that carbon nanotube (CNT)-based absorbers created using pyrolysis techniques can oxidize or lose their structural integrity at temperatures exceeding 500 °C. This limitation restricts their use in aerospace and high-power microwave systems, where thermal resilience is crucial. The sensitivity of these materials to heat presents a significant challenge for applications in defence, automotive, and aerospace industries, where consistent absorption performance is required under extreme thermal conditions.

Chemical-based microwave absorber materials face high production costs, complex fabrication processes, bulky designs, environmental hazards, and limited temperature stability. As a result, research has shifted towards sustainable alternatives. Recent studies highlight that biowaste-based materials, such as DBL, SG, coconut coir, and wood sawdust, can serve as effective microwave absorbers. These materials are low-cost, lightweight, and biodegradable, providing good microwave absorption performance. Utilizing biowaste addresses the economic and environmental drawbacks of conventional chemical-based MAMs and allows for the development of eco-friendly, efficient, and practical solutions for modern applications.

2.2 BIOWASTE-BASED MICROWAVE ABSORBER

For efficient microwave absorption, chemical-based microwave absorbers offer considerable dielectric and magnetic losses. However, despite their high performance, these conventional materials face several drawbacks, including high production costs, complicated fabrication

techniques, environmental concerns, and the requirement for bulky designs. These factors make them impractical for large-scale deployment and unsuitable for eco-friendly applications. In response to these issues, researchers have turned their attention to renewable, economical, and sustainable substitutes, which has led to the investigation and creation of microwave absorbers based on biowaste [88].

Agricultural residues like rice husk, sugarcane bagasse, coconut shell, palm kernel shell, oil palm trunk, and semi-dried banana leaves are being explored as microwave absorbing materials (MAMs) owing to their wide availability, biodegradability, and rich carbon content that enhances absorption performance [89,90]. The carbon content of the agricultural waste is shown in Table 2.2.

Table 2.2 Percentage of Carbon in various biowaste materials

Agricultural waste	Carbon %	References
Oil plum Trunk	45.91	[91]
Coco peat	65.66	[96]
Rice husk	35.77	[97]
Coconut shell	75	[92]
Sugarcane Bagasse	45.5	[95]
Corn husk	79.11	[93]
Banana leaves	43.5	[94]
Rice straw	38.24	[100]
Peanut Husk	63	[98]
Dried Bael leaves	45.8	[55]

Research has shown that bio-wastes not only have favorable dielectric properties but also meet the practical requirement of achieving RL values below -10 dB over a broad frequency range. In this context, **S.S. Pattanayak et al.** [99] examined the potential of DBL as an eco-friendly microwave absorber to mitigate electromagnetic pollution caused by excessive microwave radiation from modern electronic devices. In their study, DBL-based samples were prepared using resin and hardener (33.3 wt.%) and analyzed for microwave absorption performance at varying thicknesses (8.16 mm, 15.98 mm, and 32.02 mm) within the 1-20 GHz frequency range. Experimental results revealed that absorption performance was strongly thickness-dependent, with the 15.98 mm sample (A2) showing the best results, attaining an RL of -25.66 dB with 99.73% absorption at 1.133 GHz. Simulations further indicated improved performance, with RL reaching -31.99 dB with 99.94% absorption. Importantly, all DBL-based

samples achieved RL values below -10 dB, confirming their strong microwave absorption capability. The study concluded that DBL functions effectively as a single-layer MA, where optimization of thickness plays a critical role, though additional refinements are necessary to meet practical application requirements in electronics and communication systems

Z.S. Farhany et al. [101] proposed an eco-friendly and cost-effective approach for designing pyramidal microwave absorbers using agricultural waste-based composites to replace conventional, non-biodegradable materials such as polyurethane and polystyrene. The study utilized DBL as a filler material, combined with polyester resin (PR) and methyl ethyl ketone peroxide (MEKP) as a hardener, to improve microwave absorption performance [102]. The proposed absorber operated across a 0.1–20.0 GHz frequency and demonstrated superior performance compared to previous designs using rice husk. Specifically, rice husk-based absorbers achieved an RL of -46.172 dB within 5.0-10.0 GHz, while their performance declined to -16.031 dB at lower frequencies (0.01-1.0 GHz). In contrast, banana leaf-based absorbers exhibited enhanced absorption characteristics, achieving -63.284 dB in the low-frequency range and an RL of -123.47 dB at 4.0 GHz. These findings demonstrate how agricultural waste, especially DBL, can be used as an environmentally friendly, reasonably priced, and highly effective substitute for electromagnetic-absorbing materials in RF anechoic chamber applications.

B.S. Yew et al. [103] studied an eco-friendly microwave absorber made from coco peat, combined with polyester resin and MEKP hardener. Using an Agilent E8362B network analyzer and WR-90 waveguide, they measured dielectric properties and RL in the X-band. The composite achieved an RL of around -30 dB, attributed to the high carbon content of coco peat, demonstrating its potential as a sustainable, cost-effective microwave absorbing material.

Z. Liyana et al. [104] investigated sugarcane bagasse, an agricultural waste with high carbon content, as a sustainable microwave absorber. Dielectric properties were measured with a dielectric probe and used in CST Microwave Studio to model pyramidal absorbers. The designed absorber operated over 0.1-20 GHz and achieved a reflection loss of -45.9 dB. Compared to rice husk-based absorbers, sugarcane bagasse showed better performance, highlighting its potential as an eco-friendly, cost-effective microwave absorbing material.

H. Nornikman et al. [105] introduced a rice husk-based pyramidal microwave absorber (MA) as an alternative material for electromagnetic wave absorption. The absorber was fabricated using urea formaldehyde (UF) and phenol formaldehyde (PF) resins at varying

concentrations of 10%, 20%, and 30%. The results indicated that the proposed absorber exhibited effective absorption efficiency, with an average RL ranging from -16 to -20 dB across 1-20 GHz frequency. Furthermore, the study revealed that different resin mixtures significantly influenced the dielectric constant and return loss performance of the absorber. This work highlighted the potential of agricultural waste-based materials as cost-effective and eco-friendly alternatives to conventional microwave absorbers.

S.P. Mishra et al. [106] used coconut coir dust, a carbon-rich agricultural waste, to create eco-friendly epoxy-based microwave absorbers designed to reduce electromagnetic pollution from electronic and telecommunication systems. With a low dielectric loss of 0.25 and a dielectric constant of 3.32, the absorber showed good dielectric performance. The absorber achieved a maximum reflection loss of -23.5 dB at 10 GHz within the X-band (8.2-12.4 GHz), demonstrating coconut coir dust's potential as a sustainable and cost-effective microwave absorbing material.

S.S. Pattanayak et al. [107] examined corn husk, an abundant agricultural by-product, as a lightweight, low-cost, and eco-friendly material for microwave absorber applications. The aim of this study was to offer a sustainable alternative to conventional synthetic absorbers, which are often expensive, non-biodegradable, and raise environmental concerns. Both experimental and simulation analyses were conducted to assess the microwave absorption performance of corn husk-based composites over a range of 1-20 GHz, which includes key microwave communication bands. The corn husk-based absorber showed a maximum RL of -32.72 dB at 2.255 GHz with an optimal thickness of 5.21 mm. This significant attenuation value indicates excellent microwave absorption capabilities, especially in lower frequency range. The study also emphasized the inherent benefits of corn husk, including its low density, high carbon content, and fibrous structure, which enhance dielectric properties and improve electromagnetic wave attenuation.

S. S.S.Panda et al. [108] explored Ramphal (*Annona reticulata*) leaf ash as a sustainable and low-cost microwave absorber. Experimental results showed a maximum RL of -42.87 dB at 11.60 GHz with a 7 mm thickness, while simulations indicated an even higher RL max of -66.36 dB at 11.41 GHz for a 9.5 mm sample, achieving 100% effective absorption bandwidth. The study confirms the strong potential of Ramphal leaf ash for efficient microwave absorption applications.

S. S.S. Panda et al. [55] introduced a novel approach to study the MA behaviour of dried and sintered Bael (Aegle marmelos) leaves using 3D-printed PLA tubes. Vector network analyzer results revealed a maximum RL of -28.64 dB at 11.35 GHz for a 9 mm thick sample, with an EAB of 3.20 GHz in the X-band. Both dried and sintered samples showed strong absorption, with EAB values of 2.75 and 2.55 GHz, respectively. The integration of Bael leaf powder with PLA structures enhanced absorption efficiency, underscoring its potential as an eco-friendly microwave absorber.

M. Dou et al. [109] developed biomass-derived porous carbon from peanut shell waste using a two-step carbonization-activation process. By adjusting the carbonized peanut shell (CPS) to KOH ratio, they optimized pore structure and morphology. The best-performing sample (CPS:KOH = 1:3, 600 °C) achieved a maximum RL of -28.38 dB with a 2.58 GHz effective absorption bandwidth at 2.5 mm thickness. The high surface area (1037.589 m²/g) and porous architecture promoted conductive networks and multiple electromagnetic wave reflections, enhancing absorption efficiency.

The study demonstrates the potential of using renewable biomass to produce effective and environmentally friendly MAM, which combines high absorption performance with sustainability and cost-effectiveness.

Table 2.3 Microwave Attenuation Characteristics of Biowaste-Based Absorbers

Material	Shape	Thickness (mm)	Frequency (GHz)	Reflection loss (dB)	reference
Banana leaves	Pyramidal	20	2-18	-50	[101]
Banana leaves	Single	32.02	1-20	-25.66	[99]
bael leaves	Single	9	8-12.5	-28.64	[55]
Corn husk	Single	5.21	1-20	-30.72	[107]
Cocopeat	Single	6	8.2-12.4	-30	[103]
Sugarcane Bagasse	Pyramidal	20	1-20	-30	[104]
Rice husk	Pyramidal	10.40	1-20	-16	[105]
Ramphal leaves	single	9.5	8.2-12.4	-42.87	[108]
Coconut coir dust	single	3	8.2-12.4	-23.5	[106]
Sugarcane bagasse	Single	6	8.2-12.4	-22.8	[95]
Peanut shell	Single	2.5	2.58	-28.38	[109]

Overall, these studies emphasize agricultural waste as a promising, low-cost, and environmentally friendly alternative to traditional MAMs. These biowaste materials naturally

contain high carbon content, which enhances their favourable dielectric properties and enables efficient attenuation of electromagnetic waves.

Among the materials reported, DBL showed the most promising performance, especially when formed into pyramidal structures. They achieved an impressive RL of -50 dB across the 2-18 GHz range at a thickness of 20 mm. Similarly, dried bael leaves and ramphal leaves demonstrated excellent absorption characteristics in X-band, with RL values of -28.64 dB and -42.87 dB, respectively, at thicknesses of around 9 mm. Corn husk demonstrated an RL of -30.72 dB at a relatively thick thickness of 5.21 mm, while coco peat produced similar results (-30 dB) at a thickness of 6 mm at X-band. Sugarcane bagasse, used in both pyramidal and single-layer structures, achieved RL values ranging from -22.8 dB to -30 dB across a frequency spectrum of 1 to 20 GHz. This indicates strong absorption capabilities at thicknesses of 20 mm and 6 mm, respectively. In contrast, rice husk-based absorbers showed moderate performance, with an RL of -16 dB, suggesting limitations in their dielectric properties compared to other agricultural waste materials. In addition, coconut coir dust and absorbers made from peanut shells demonstrated excellent absorption performance -23.5 dB and -28.38 dB, respectively at thicknesses between 2.5 and 3 mm.

Overall, these findings confirm that absorbers made from biowaste can achieve high microwave absorption performance. However, these materials have some limitations, including low electrical conductivity, moisture sensitivity, non-uniform properties, mechanical weakness, and limited thermal stability. Tackling these issues will necessitate additional optimization for real-world applications.

2.2.1 CHALLENGES RELATED TO FABRICATED BIOWASTE-BASED MAMs

Biowaste-derived MAMs are considered eco-friendly, cost-effective, and lightweight alternatives to traditional chemical-based absorbers. However, despite these advantages, biowaste-based MAMs face several limitations that hinder their large-scale implementation and optimization of performance. The main challenges are outlined below.:

2.2.1.1 Low Electrical Conductivity

Biowaste materials are mainly composed of cellulose, hemicellulose, and lignin, all of them being insulating and have low dielectric loss. This results in a weak capability to attenuate electromagnetic waves. Effective microwave absorption generally requires both dielectric and conductive loss mechanisms; however, pure biowaste does not possess sufficient electrical conductivity to achieve this balance [10][111]. To enhance the performance of biowaste absorber conductive fillers like carbon nanotubes (CNTs), graphene, charcoal, coal, or ferrite

particles are frequently added to biowaste matrices. While these additions improve absorption properties, they also elevate material costs and fabrication complexity [112].

2.2.1.2 Limited Thermal Stability

Biowaste materials are organic and begin to degrade at high temperatures. This degradation restricts their application in high-temperature environments, such as aerospace and defence. The thermal degradation not only reduces their dielectric properties but also compromises their structural integrity, leading to decreased absorption efficiency. While carbonization can improve thermal stability and conductivity, it requires high temperatures and significant energy consumption, which somewhat undermines the environmental benefits.

2.2.1.3 Moisture Sensitivity and Poor Durability

Biowaste-derived materials are hydrophilic due to hydroxyl groups in cellulose, resulting in high moisture absorption. This negatively impacts dielectric properties, interfacial polarization, and the overall performance of microwave absorption [113]. Furthermore, moisture ingress leads to dimensional instability and microbial degradation, which further diminishes mechanical strength and durability. Surface functionalization and polymer encapsulation can address this issue, but these processes increase costs and reduce sustainability [103].

2.2.1.4 Mechanical Weakness and Structural Integrity Issues

Raw biowaste has low mechanical strength, restricting its use in structural or vibration-sensitive applications [105]. When used in powdered form for composites, biowaste requires polymer binders or resin matrices for structural support, which increases thickness and weight. This requirement affects the design of lightweight, thin absorbers, making them less suitable for compact electronic and aerospace applications.

1 Biowaste-based microwave absorbers provide an eco-friendly and cost-effective alternative to conventional chemical-based MAMs [114]. However, they encounter several limitations, such as low electrical conductivity, high moisture sensitivity, variability in material properties, limited thermal stability, and poor mechanical strength. To tackle these challenges, it is essential to incorporate conductive fillers into biowaste materials to create composites. This approach improves microwave absorption, electrical conductivity, thermal stability, and mechanical strength. Additionally, techniques such as hybridization with conductive or magnetic fillers, surface modification, and optimized processing can enhance performance.

2.3. BIO COMPOSITE-BASED MICROWAVE ABSORBER

Bio-composite microwave absorbers have emerged as promising materials that combine agricultural or biomass-derived fillers with conductive and magnetic additives to achieve efficient electromagnetic wave attenuation. These composites utilize the natural carbon content and porous structure of biowaste materials such as DBL, SG, coconut coir, rice husk (RH), and peanut shells [55]. This provides a lightweight and eco-friendly base. Despite their potential, biowaste materials face significant limitations, including low electrical conductivity, high moisture absorption, and restricted thermal stability. These factors hinder their effectiveness in high-frequency applications when used independently.

To overcome these limitations, researchers have introduced conductive fillers such as graphene, graphite, coal, charcoal, MWCNTs, and magnetic nanoparticles into biowaste materials [115]. This composite greatly improves dielectric and magnetic losses, resulting in enhanced RL and broader bandwidth performance [116]. For example, **H.Kaur et al.** [117] explored the improvement of microwave absorption in pyramidal absorbers by developing a composite of RH and coal, aiming to enhance the performance of conventional RH-based absorbers used in radio frequency anechoic chambers. The study utilized CST Microwave Studio simulations and experimental validation through dielectric probe and radar cross-section methods. The researchers compared the absorption performance of pure rice husk to rice husk–coal composites over the 0 to 20 GHz range. The composite absorber showed excellent performance, with an RL of -44 dB at 10 GHz in 8.2-2.4 GHz. This research shows inclusion of coal with rice husk significantly enhances absorption efficiency, making it a promising and sustainable alternative for reducing electromagnetic interference in RF applications.

L. Zahid et al. [118] designed an MA by combining sugarcane bagasse with rubber tire dust for EMI shielding in the Ku-band (12.418 GHz). The study aimed to utilize agricultural and industrial waste to design economical and sustainable absorbers. The study analyzed dielectric properties along with the reflection (S_{11}) and transmission (S_{21}) coefficients. Experimental results showed that the SG-rubber tire dust composite achieved an average reflection coefficient of -16 dB, outperforming -4.98 dB for pure SG. This improvement suggests enhanced microwave absorption performance. The study highlights SG-rubber tire composites as a sustainable option for EMI shielding and microwave absorption in high-frequency applications.

M.F.B. Malek et al. [119] studied the use of rubber tire dust combined with RH to improve pyramidal microwave absorbers for RF anechoic chambers. The high carbon content in both materials enhances microwave absorption. Three composite formulations were tested via an

open-ended coaxial method across 7–13 GHz. The optimal blend (25 wt.% RH and 75 wt.% coal, 20 mm thick) achieved a maximum average RL of -35 dB, outperforming conventional absorbers. The study demonstrates the potential of using agricultural and industrial waste to create cost-effective, eco-friendly MAM for electromagnetic compatibility applications.

Y.S. Lee et al. [120] investigated rice husk-carbon nanotube (RHCNT) composites as advanced microwave absorbers, leveraging the high carbon content of both materials. Composites with varying rice husk-to-CNT ratios showed increased dielectric constant and loss factor, enhancing absorption performance. Complex permittivity was measured with an Agilent dielectric probe, and reflection and transmission losses were evaluated using the rectangular waveguide method. The RHCNT composites achieved a reflection loss of -20 dB in the 12.4–18 GHz range, outperforming pure RH absorbers, highlighting the potential of combining agricultural waste with conductive nanomaterials for sustainable, high-performance microwave absorption.

R. Kaur et al. [121] examined the use of banana leaves as an eco-friendly material for creating pyramidal microwave absorbers. To improve absorption capability across a wider frequency range, carbon-rich coal was incorporated into the design. The study utilized software simulations in CST Microwave Studio and involved sample fabrication using cobalt as an accelerator. Performance evaluation was conducted through the free-space measurement method over X-band. The banana leaves-coal composite demonstrated excellent absorption, with an average RL of -45.2 dB across 0-20 GHz, making it an efficient and sustainable alternative to conventional commercial absorbers.

Y.S. Lee [122] developed single-layer microwave absorbers by combining RH with MWCNTs at 3, 5, and 15 wt% ratios. Dielectric properties were measured using a rectangular waveguide, and absorption performance was evaluated via free-space measurements in the X-band. Increasing MWCNT content improved dielectric constant and loss factor, while magnetic properties remained unchanged ($\mu_r = 1 - j0$). The RH-CNT3 composite achieved 99.8% absorption (-29.06 dB) at 9.75 GHz with 8 mm thickness. Increasing the thickness to 9 mm shifted the peak to 8.85 GHz, with 99.4% absorption with RL of -22.34 dB, showing that thicker samples shift absorption peaks to lower frequencies.

N.F.N. Yah et al. [123] studied eco-friendly composites made from coconut coir and charcoal powder with epoxy resin and hardener for electromagnetic wave absorption. Dielectric properties were measured using a two-port waveguide over the X-band. Composites showed an average permittivity of 3.00, with 10 wt% charcoal reaching 3.59. The 20 wt% charcoal

composite exhibited excellent absorption, achieving RL below -5 dB (>99% absorption) in the X-band, demonstrating the potential of coconut fiber-based composites as sustainable and efficient microwave absorbers.

Y.S. Lee et al. [124] studied single-layer microwave absorbers made from rice husk ash (RHA) with varying CNT content to improve absorption efficiency and reduce thickness. Composites included pure RHA, RHA/CNTs-1 (1 wt%), RHA/CNTs-2, and RHA/CNTs-5 (5 wt%). Dielectric properties were measured using an Agilent probe with 85070E software over 2–18 GHz. Pure RHA (10 mm thick) showed a maximum RL of -8 dB at 10.8 GHz, whereas CNT-filled composites exhibited significantly better performance at reduced thicknesses. RHA/CNTs-1 (9 mm) reached -40 dB at 10.2 GHz, and RHA/CNTs-5 achieved -27 dB at 11.5 GHz with only 2 mm thickness. Optimized thicknesses of 3–4 mm for RHA/CNTs-5 provided RL values of -40 to -33 dB, while thicker samples (>5 mm) suffered from impedance mismatch. The RHA/CNTs-5 composite maintained RL < -10 dB from 10–13.7 GHz, showing broader absorption than pure RHA. These results confirm that integrating CNTs into RHA enhances dielectric loss, improves impedance matching, and enables lightweight, broadband absorber designs.

S.S. Pattanayak et al. [125] studied microwave absorbers based on corn husks, examining the effect of adding varying charcoal content on absorption performance over 1–20 GHz. Dielectric properties and S_{11} were measured with an open-ended coaxial probe, and simulations were performed in CST Microwave Studio. The composite with charcoal achieved an RL of -50.27 dB at 19.22 GHz, showing significant improvement over pure corn husk. Both experimental and simulation results highlight corn husk-charcoal composites as promising, eco-friendly, and low-cost microwave-absorbing materials for electronic and communication applications.

S.S. Pattanayak et al. [126] developed a single-layer microwave absorber using DBL with a minimal thickness of 1.5 mm, operating over 1–20 GHz. The study examined the effect of charcoal filler on dielectric properties and absorption performance. Increasing charcoal content enhanced dielectric constant, conductivity, and lossy characteristics, improving absorption. Dielectric properties and S_{11} were measured via an open-ended coaxial probe, and simulations were performed in CST Microwave Studio. The composite achieved a maximum RL of -25.92 dB at 3.337 GHz, corresponding to 99.74% absorption. While the absorption bandwidth at low frequencies was narrow, it can be improved by increasing charcoal content. Both experimental and simulated results confirm that DBL/charcoal composites are sustainable, cost-effective alternatives suitable for anechoic chambers and lightweight antenna substrates.

S.S.Pattanayak et al. [127] developed a double-layer microwave absorber using corn husk, designed for 1–20 GHz. The first layer acted as an impedance-matching layer, while the second, lossy layer, charcoal content was varied to optimize absorption. Dielectric properties and S_{11} were measured with an open-ended coaxial probe, and simulations were conducted in CST Microwave Studio. XRD analysis confirmed amorphous carbon in corn husk, enhancing electromagnetic wave attenuation. All samples achieved RL below -10 dB (>90% attenuation), with the best configuration (DL2) reaching -49.04 dB at 18.271 GHz and DL1 achieving -44.78 dB at 14.528 GHz. Increasing charcoal content improved both impedance matching and absorption, highlighting the potential of corn husk double-layer absorbers as lightweight, eco-friendly, and cost-effective microwave absorbing materials.

S.S. Pattanayaket. al.[128] developed a double-layer microwave absorber using DBL and charcoal powder for 1-20 GHz. Dielectric properties were measured with an open-ended coaxial probe and vector network analyzer over 1-16 GHz. Two single-layer absorbers (4 mm each) and one double-layer absorber (8.02 mm) were tested. The double-layer design showed superior absorption, achieving a maximum RL of -32.61 dB at 8.341 GHz, due to improved impedance matching and higher dielectric loss, demonstrating its potential as a lightweight, eco-friendly alternative to conventional microwave absorbers.

D. Gupta [129] investigated microwave-absorbing composites made from RH and exhausted activated charcoal (EAC) from water filters as a cost-effective solution. Samples were prepared using a planetary ball mill, and XRF and particle size analyses characterized their composition and morphology. Dielectric properties were measured with a vector network analyzer over 2-18 GHz. The RHC-11 sample (20 wt% EAC) achieved the highest RL of -38.3 dB at 12 GHz with 14 mm thickness. A layered metamaterial absorber using copper patches, FR4 substrate, and resistive ink achieved a 6.60 GHz absorption bandwidth (12.16-18.76 GHz) at only 2.3 mm thickness, with peak absorptivity of 99.34% at 16 GHz. The design showed angle- and polarization-independent performance, highlighting its potential for anechoic chambers and EMI shielding applications.

Y.S. Lee, 130] studied rice husk ash/polyester (RHAP) composites for microwave absorption in the Ku-band. Composites with 40–80 wt% RHA were fabricated and characterized using a rectangular waveguide method with Agilent 85071E software, and modeled in CST Microwave Studio. Increasing RHA content raised both dielectric constant and loss factor, enhancing absorption. The 80 wt% RHA composite (15 mm thick) achieved a maximum RL of -28.4 dB at 13.81 GHz, corresponding to 99.84% absorption, with an effective bandwidth (RL < -10 dB)

in the X-band. These results indicate RHAP composites are eco-friendly and effective microwave absorbers for Ku-band applications.

Y.S. Lee et al.[131] proposed multilayer microwave absorbers using rice husk (RH) and carbon nanotube (CNT) composites to achieve wideband absorption. Dielectric properties of each layer were measured and used to optimize designs in CST Microwave Studio, tested over 2–18 GHz. Reflectivity analysis showed improved absorption when a highly lossy composite was placed in the bottom layer. Two multilayer configurations were studied: one with three equal 0.5 cm layers of varying dielectric properties, and another with layers of 0.5 cm (L1) and 1 cm (L2, L3). The 1.5 cm absorber achieved multiple bands with RL < -10 dB, especially when L2 was replaced with a lossy RHA/CNT-1 composite. The 2.5 cm design showed even broader multi-band absorption and improved reflection loss due to multiple resonances. This study confirms that RH/CNT multilayers provide superior broadband absorption for electromagnetic interference mitigation compared to single-layer designs.

Y.S Lee et al.[132] proposed a single-layer microwave absorber made from rice husk (RH) and carbon nanotube (CNT) composites for 12.4-18 GHz. Composites with varying CNT content were characterized using an Agilent dielectric probe, and absorption performance was evaluated via rectangular waveguide measurements. Pure showed moderate absorption that improved with thickness, while RH-CNT composites exhibited significantly enhanced absorption due to higher dielectric constant and loss factor. The 5 wt% CNT composites achieved 88.9% absorption across 12.4-18 GHz. The study demonstrated that adding CNTs improves absorption efficiency and allows reduced absorber thickness, offering an eco-friendly approach to recycling agricultural waste for high-performance microwave absorbers in EMI mitigation.

P.P. Singh et al.[133] developed a hybrid microwave absorber using banana stem (BAN) and RH dust for X-band applications. The 50:50 composite (particle size 150 µm) was prepared via NaOH treatment, ultrasonication, and incorporation into an epoxy matrix by hand layup. The 3 mm thick absorber achieved an RL of -4.01 dB at 11 GHz, corresponding to 96.02% EM power attenuation and a 2.13 GHz bandwidth. SEM, EDS, and FTIR analyses confirmed impurity removal and a porous structure that enhances absorption. The composite exhibited good impedance matching ($Z_{in}/Z_0 = 0.55$) and significant dielectric and tangent losses due to the heterogeneous fiber distribution. Distinct resonant peaks and FWHM differences indicated multiple absorption mechanisms. The BAN/RH hybrid provides lightweight, broadband absorption, making it suitable for stealth applications and EMI shielding.

K. Sivakumaret al. [134] developed an epoxy-based bio composite for EMI shielding, incorporating peanut husk-derived carbon quantum dots (CQDs) and ferrite foil to enhance X- and Ku-band microwave absorption. Composites were fabricated via hand layup at room temperature, and their dielectric, magnetic, and mechanical properties were evaluated. Adding 45 vol.% ferrite foil increased relative permeability to 4.62 and dielectric loss to 0.072, while CQDs further improved performance. The EFC3 composite (5 vol.% CQDs) showed the highest relative permittivity and dielectric loss, increasing by 65% and 66% over pure epoxy, respectively. Magnetic hysteresis improved, with EFC1 (1 vol.% CQDs) reaching 728×10^{-6} emu magnetization. EFC3 achieved maximum microwave shielding effectiveness of -52.8 dB (E band) and -54.7 dB (J band). These results demonstrate that combining ferrite foil and CQDs provides excellent EMI shielding, mechanical strength, and lightweight properties, suitable for aerospace, radar, telecommunications, and electronic applications.

Table 2.4. Reflection Loss and Absorption Performance of Biowaste Composite Absorbers

Material	Composite	Dielectric constant	Thickness	Frequency (GHz)	Reflection loss (dB)	Bandwidth (GHz)	reference
Banana leaves	Charcoal 0.028wt%	5.23	1.50mm	1-20	-25.29	0.8	[126]
Corn husk	Charcoal 4.44wt. %	3.9	1.08mm	1-20	-50.2	1.6	[125]
Rice husk	Coal 60wt.%	2.50	20mm	8.2-12.4	-44	-	[117]
Rice husk	Rubber tire dust 75wt.%	3.43	20mm	7.0-13.0	-35	-	[119]
Rice husk ash	polyester	4.80	15mm	12.4-18	-28.4	0.81	[130]
Rice husk ash	CNTs 5wt%	5.586	3mm	2-18	-40	3.2	[124]
Double layer Rice husk	CNTs 5 wt.%	7.08	10mm	2-18	-37.2	5.1	[131]
Rice husk	CNTs 5 wt.%	3.96	5mm	12.4-18	-32	3.6	[132]
Sugarcane bagasse	Rubber tire dust 50 wt.%	3.38	5mm	12.4-18	-16	-	[118]
Banana leaves	Coal 40wt.%	2.018	$W \times L \times H = 15 \times 15 \times 13(\text{cm}^3)$	0-20	-38.4	-	[121]
Banana stem	Rice husk dust 50wt.%	3.2	3mm	8.2-12.4	-14.01	2.13	[133]
Rice husk	Activated Charcoal 30wt.%	5.3	14mm	2-18	-38.3	-	[129]

Peanut husk	Ferrite foil 45wt. %	4.62	3mm	2-3 10-20	-52.8 -54.7	-	[134]
-------------	-------------------------	------	-----	--------------	----------------	---	-------

Table 2.4 provides a summary of the reflection loss and absorption performance of biowaste composite absorbers. The reviewed studies demonstrate that these composites offer significant promise as sustainable, cost-effective, and environmentally friendly alternatives to traditional MAMs. Incorporating agricultural waste such as RH, corn husk, DBL, SG, and peanut husks, combined with fillers like carbon nanotubes (CNTs), charcoal, coal, and magnetic particles, significantly enhances their microwave properties. This improvement effects in better absorption of electromagnetic waves. Among the reported materials, RHA/CNT composites showed outstanding performance, attaining an RL of -40 dB at only 3 mm thickness, while pure RHA required 10 mm to reach a lower absorption level. Corn husk-charcoal composites achieved a remarkable RL of -50.2 dB at just 1.08 mm thickness, demonstrating strong absorption across 1-20 GHz. Banana leaves-based absorbers also performed well, with RL values of -38.4 dB for single-layer composites and -32.61 dB for double-layer designs, underscoring the benefits of impedance matching. Additionally, epoxy composites reinforced with ferrite foil and peanut husk-derived carbon quantum dots demonstrated excellent EMI shielding, ranging from -52.8 to -54.7 dB in the E and J bands, while also improving mechanical strength. Multi-layer structures made from rice husk-CNT composites achieved broad bandwidths of up to 5.1 GHz, outperforming single-layer designs.

These results indicate that biowaste-based composites provide high absorption efficiency, reduced thickness, and a wide bandwidth, all while being lightweight and environmentally friendly. Many current designs rely heavily on fillers such as charcoal, coal, or carbon nanotubes (CNTs), which decreases their eco-friendliness and increases costs. Future efforts should focus on developing composites that use minimal fillers while still maintaining strong absorption properties. This approach will help create solutions that are both cost-effective and sustainable.

2.4. GAPS IN PRESENT STUDY

According to the literature review, it has been observed that extensive research has been carried out on microwave absorbing materials (MAMs), particularly those based on chemical materials such as ferrites, Ni-Co alloys, cobalt, nickel, and polymers. These materials demonstrate strong electromagnetic absorption properties; however, they have significant drawbacks, including non-biodegradability, high cost, heavy weight, and potential toxicity at high temperatures. To

1 address these challenges, researchers are exploring biowaste-based microwave absorbers as sustainable and eco-friendly alternatives. Agricultural residues, such as RH, DBL, SG, coconut peat, and corn husks, have demonstrated promising results when combined with conductive fillers like charcoal and coal. These composites exhibit improved microwave properties, leading to enhanced microwave absorption performance.

Despite these advancements, there are still several gaps in the current state of research.

2.4.1 Limitations of Traditional Microwave Absorbers

Traditional materials such as Ni-Co alloys, ferrites, and polymers have been commonly used for microwave absorption. While these materials are effective, they pose several issues: they are non-biodegradable, environmentally hazardous, and expensive. Additionally, they tend to be heavier, which limits their use in lightweight applications like aerospace. Thus, there is a growing need to focus on sustainable, lightweight, and cost-effective alternatives derived from biowaste that can offer comparable or even superior absorption characteristics.

2.4.2 High Additive Usage in Biowaste Composites

Many biowaste-based absorbers, such as those made from banana leaves, corn husks, and sugarcane bagasse, typically require a high content of additives like charcoal, coal, or ferrite (30–50 wt.%) to achieve effective absorption. However, this excessive reliance on additives increases costs and decreases eco-friendliness. There are limited studies that explore the reduction of filler content while still maintaining high performance. Therefore, future research should focus on the potential of using very small amounts of CNTs or other high-efficiency fillers to enhance absorption while ensuring environmental sustainability and cost-effectiveness.

2.4.3 Underexplored Composites: Dried Banana Leaves (DBL) and Sugarcane Bagasse with CNTs

While rice husk combined with CNTs has shown excellent performance, other agricultural wastes, such as dried banana leaves (DBL) and sugarcane bagasse, have not been thoroughly studied in combination with CNTs. This presents an opportunity to design and evaluate hybrid composites of DBL-CNT and sugarcane bagasse-CNT for improved microwave absorption. Optimizing their thickness, loading ratios, and dielectric properties can greatly enhance their performance.

2.4.4 Limited Study on Temperature Variations

Most current research assesses the performance of microwave absorbers under standard laboratory conditions, often overlooking real-world environmental factors like temperature fluctuations. Since the performance of microwave absorbers can be affected by temperature

changes, it is crucial to examine the thermal stability and absorption behaviour of biowaste-based composites in different thermal environments. Such analysis is necessary for ensuring reliable performance in real-world applications, such as military and aviation systems.

This work aims to develop and analyze an eco-friendly and cost-effective microwave absorber using agricultural residues, specifically dried banana leaves and sugarcane bagasse, along with a minimal amount of carbon nanotubes (CNTs). The focus is on enhancing the absorption properties while ensuring environmental sustainability, and it also includes an investigation of how temperature variations affect the material's performance.

2.5. OBJECTIVES OF PROPOSED WORK

The following objectives have been proposed and included in the research. These objectives are based on earlier research, provided literature review, and existing knowledge:

1. To study and analysis of magnetic and dielectric properties of different types of agriculture waste and Carbon Nanotubes materials as microwave absorber.
2. To develop dried banana leaves/CNT and sugarcane bagasse/CNT based composite materials and investigate their absorption properties.
3. To examine the impact of thermal aware environment conditions on developed composite materials and analyse their microwave absorbing properties

2.6. RESEARCH METHODOLOGY

The following aspects will be included in work to be done for methodology for suggested proposal.

1 Firstly, study and analysis of Microwave Absorption Properties of Agricultural Waste Materials (Sugarcane Bagasse and Dried Banana Leaves). Based on the literature review, rice husk has been the only agricultural waste material previously combined with CNTs for microwave absorption applications. This study explores SG and DBL as novel agricultural waste materials for microwave absorption. First, SG and green banana leaves were collected, washed, and sun-dried for 25-30 days to remove moisture. The dried materials were ground into a fine powder and sieved to ensure uniform particle size. The chemical composition of the powders was analysed using a CHNS analyser to determine their elemental composition. For composite fabrication, the powdered SG and DBL were mixed with PR as a binding agent, MEKP as a hardener, and cobalt as an accelerator. Mixtures were ultrasonicated for 30–35 minutes to ensure uniform dispersion before being poured into a rectangular aluminium Mold (22.86 mm × 10.16 mm × 2 mm) and cured for 24 hours at room temperature. Multiple samples

with varying thicknesses were prepared for further analysis. Structural characterization was performed using SEM to examine surface morphology and particle size distribution. The dielectric properties and reflection loss (S_{11} parameter) of raw SG and DBL were measured using a VNA in the X-band frequency range to assess their effectiveness as natural microwave absorbers.

Next, synthesis and characterization of Sugarcane Bagasse/CNT and Dried Banana Leaves/CNT Composites. MWCNTs were used as a conductive filler to enhance the microwave absorption properties of the composites. PR was used as a binding agent, while MEKP served as a hardener, and cobalt acted as an accelerator. To prepare the composite, MWCNTs were mixed with dried banana leaves (DBL) and sugarcane bagasse (SG) powders at different weight ratios of 1 wt.%, 3 wt.%, and 5 wt.%. The composite mixtures were ultrasonicated for 30–35 minutes to uniformly disperse MWCNTs. Once homogeneous, the mixture was poured into a rectangular aluminium mold and cured at room temperature for 24 hours.

The microstructural properties of the DBL-MWCNT and SG-MWCNT composites were analysed using SEM to study their morphology and particle dispersion. To evaluate the microwave absorption performance, measurements were conducted using the rectangular transmission line technique at 8.2–12.4 GHz. The absorption performance of the synthesized composites was compared with raw DBL, SG, and previously studied RH-CNT composites to evaluate their effectiveness as novel microwave absorbers.

After studying and analyzing all fabricated samples, the best of all fabricated samples was selected. Their microwave absorption properties were analysed across various temperatures (20°C–120°C). A heating plate was used to control the temperature of the samples. An infrared thermometer was used to measure the exact surface temperature of the samples. A metal back plate was placed behind the samples to prevent microwave transmission, ensuring accurate S measurements. The one-port VNA was used to measure the S_{11} parameter.

At last, the study compared the absorption efficiency of DBL, SG, DBL-MWCNT, and SG-MWCNT composites with commercial microwave absorber materials.

CHAPTER 3

FUNDAMENTALS OF MICROWAVE ABSORPTION

This chapter mainly focuses on understanding the fundamental principles of microwave absorption and analyzing the dielectric and magnetic properties of agricultural waste materials and carbon nanotubes (CNTs) used as microwave absorbers. The chapter begins with a basic introduction to microwave absorbers and explains their importance in reducing electromagnetic interference. It further describes how parameters such as dielectric properties, impedance matching, thickness, conductivity, and particle size influence absorption performance. Different polarization mechanisms responsible for dielectric loss and energy dissipation are also discussed. Finally, the chapter presents the experimental analysis of three agricultural wastes, namely sugarcane bagasse (SG), dried banana leaves (DBL), and teak wood sawdust (TWSD), followed by the study of dielectric properties of carbon nanotubes (CNTs) to highlight their role in improving the microwave absorption.

3.1. Microwave absorber

In the modern world, technology is an essential component of our existence. Whether using GPS, point-to-point communication, radar systems, mobile phones, satellite TV, or wireless internet (Wi-Fi), all of these devices and systems use microwave frequencies to make their connections. These microwave signals propagate through the atmosphere as part of the electromagnetic spectrum, which encompasses not only visible light but also radio waves, X-rays, and other forms of radiation [135]. With the increasing use of electronic devices and wireless systems, humans are constantly surrounded by electromagnetic (EM) radiation. From smartphones, laptops, and smartwatches to mobile towers, Bluetooth speakers, and home routers, every device either sends or receives EM signals. This continuous exposure has led to growing concerns about electromagnetic pollution (EM pollution), which refers to the undesired presence of electromagnetic waves in the surrounding environment. This pollution can harm electronic systems and may pose risks to human health. It may disrupt the functioning of electronic equipment by introducing unwanted signals, creating interference or noise, and potentially leading to long-term deterioration of the device's components [136]. More importantly, prolonged exposure to intense electromagnetic radiation has been linked to several health problems, such as headaches, sleep disturbances, stress, nausea, and persistent fatigue. In some instances, people may experience serious health issues such as depression, tinnitus, and other brain-related problems. As wireless communication and smart technologies evolve

rapidly, managing electromagnetic (EM) pollution has become a critical concern. To tackle this challenge, specialized materials called microwave absorber materials are being utilized. These materials are specifically designed to absorb unwanted electromagnetic waves, thereby reducing their harmful effects on electronic devices, communication systems, and the surrounding environment.

3.1.1 Importance of Microwave Absorbers in Modern Applications

Microwave absorber materials are becoming increasingly important in today's digital era, as they effectively mitigate the harmful effects of EM radiation. These materials absorb incoming electromagnetic waves and convert their energy, primarily into heat, rather than reflecting them back or allowing them to pass through. In simple terms, it behaves like a sponge that absorbs excess radiation, preventing it from spreading further. As illustrated in Figure 3.1, when an electromagnetic wave interacts with a microwave-absorbing material, it goes through several processes.

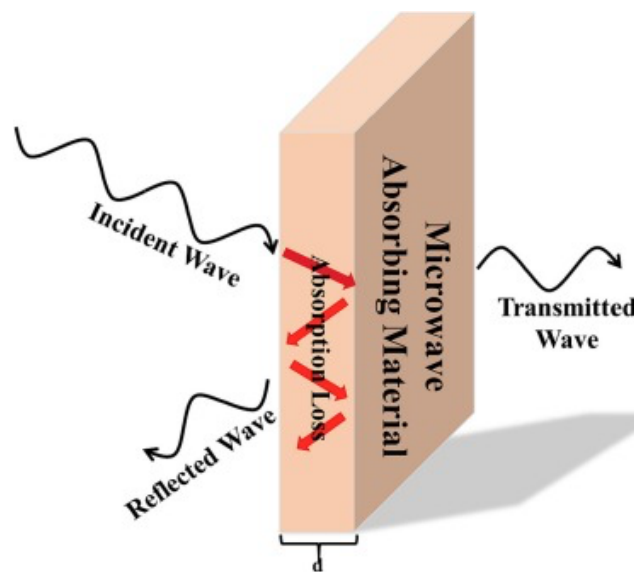


Figure 3.1 Microwave absorber material [138]

The electromagnetic wave that approaches and affects the absorber's surface is known as the incident wave, and it is the first component. When the wave makes contact, a portion of its energy is reflected back into the surrounding medium. This is known as the reflected wave and represents the part of the incident wave that does not enter the material, instead bouncing off the surface. Another component of the wave is able to pass through the material and continues on the other side; this is called the transmitted wave. The most crucial aspect of this interaction is the energy that penetrates and remains within the material. This component of the wave is

20 absorbed by the material and is primarily converted into heat. This phenomenon is referred to as absorption loss, which is the desired outcome for efficient microwave absorbers. The goal is to maximize this absorption while minimizing reflection and transmission, ensuring that the electromagnetic energy is effectively contained and neutralized within the absorbing medium. The absorption of certain materials is particularly beneficial because it helps reduce interference between electronic devices, protects sensitive components from electromagnetic stress, and decreases radiation exposure for humans. These materials are especially valuable in high-radiation environments such as airports and aircraft, where they assist with radar management; military equipment, where they support stealth operations; satellite and communication systems; and hospitals and medical laboratories, where they prevent interference with diagnostic tools. Additionally, they are useful in homes and workplaces with multiple wireless devices operating simultaneously. Beyond providing protection, these materials enhance the overall performance and reliability of electronic systems by maintaining clear signals and preventing operational errors or damage. Overall, the goal of microwave absorber materials is to maximize absorption while minimizing reflection and transmission, ensuring that the electromagnetic energy is effectively contained and neutralized within the absorbing medium.

3.1.2 Key Characteristics of Effective Microwave Absorbers

For optimal performance, a microwave absorber material must fulfil several key properties. The following properties are deemed essential.

3.1.2.1 High Absorption Capability:

One of the key features of the material is its ability to absorb a significant amount of microwave energy. This capability depends on two main properties: dielectric permittivity and magnetic permeability. Dielectric permittivity measures how the material responds to an electric field, while magnetic permeability assesses its response to a magnetic field. The more balanced these two properties are, the more effectively the material can absorb radiation.

3.1.2.2 Impedance Matching:

16 61 For a material to efficiently absorb radiation, its impedance should be closely matched to that of free space (air) to reduce reflection at the interface between the air and the absorber [139]. If the impedance is mismatched, microwaves tend to reflect off the surface rather than being absorbed. Proper impedance matching ensures that more radiation enters the material and is efficiently attenuated inside [140].

3.1.2.3 Good Electrical Conductivity:

Materials with appropriate electrical conductivity can enhance dielectric losses, which aids in attenuating incoming electromagnetic waves more effectively.

1.1.2.4 Stable at High Temperatures:

The material must be able to endure heat and mechanical stress for extended periods of use. EM absorbers are commonly utilized in devices that generate heat or in outdoor settings where temperature fluctuations are frequent. A reliable absorber should not deteriorate under these conditions

1.1.2.5 Lightweight and Thin:

For practical applications, particularly in mobile or aerospace settings, the material should be lightweight and compact. A thin design offers greater flexibility, simplifies installation, and does not add unnecessary weight to the device or system.

1.1.2.6 Environmentally Friendly and Cost-Effective:

In recent years, agricultural waste materials have attracted interest due to their eco-friendliness, low cost, and sustainability. Biowaste materials such as banana leaves, rice husks, coconut shells, and sugarcane bagasse can be processed into effective absorbent materials. These materials are biodegradable, widely available, and help reduce dependence on synthetic, often toxic, substances.

Designing microwave absorber materials necessitates careful attention to their dielectric, magnetic, and conductive properties to ensure effective wave absorption while minimizing reflection. The overall performance of an absorber relies on the efficient tuning and integration of its properties within the material. Hence, choosing the right base materials is essential not just for achieving strong absorption capabilities but also for guaranteeing the material's mechanical strength, heat resistance, and secure attachment to supporting surfaces in real-use conditions. While Metals have traditionally been favored for their excellent electrical conductivity, their weight and susceptibility to corrosion limit their practicality in many modern applications. As a result, there has been a growing trend toward using lightweight and multifunctional alternatives, such as various polymers and carbon-rich composites. Among these, Carbon-based materials are exceptional due to their ability to act as conductors, semiconductors, or insulators depending on their structure. This versatility makes them highly adaptable for microwave absorption. Natural agricultural residues, such as rice husk, coconut peat, and ramphal leaves, are excellent sources of carbon and provide a sustainable, low-cost option for fabricating absorbers. These materials not only facilitate the desired electromagnetic loss mechanisms but also offer environmental benefits, as they are biodegradable, renewable,

and readily available. By incorporating functional fillers such as carbon nanotubes or ferrite particles, the efficiency of bio-based absorbers can be significantly enhanced, establishing a strong balance between performance and environmental responsibility. As wireless technologies continue to expand and concerns over electromagnetic interference intensify, the need for efficient and eco-friendly microwave absorbers has become increasingly important. In this regard, utilizing agricultural waste as a source material presents a sustainable and innovative approach for designing next-generation microwave-absorbing materials [141].

3.2 Role of Dielectric Properties and Magnetic Properties in Microwave Absorber Performance

The dielectric characteristics of a material are fundamental in governing how it interacts with electromagnetic waves [142]. In the case of MAMs, the dielectric behaviour determines how well a material can store and dissipate electrical energy when exposed to an alternating electromagnetic field.

The dielectric behaviour of a material is explained by its complex permittivity, represented as ϵ .

$$\epsilon = \epsilon' - j\epsilon'' \quad 3.1$$

Where ϵ' represents the real part of permittivity, also known as the dielectric constant, which indicates a material's capacity to store electrical energy. ϵ'' represents the imaginary part, also known as the dielectric loss factor, which indicates the material's ability to dissipate energy by converting electromagnetic energy into heat [10]. $j = \sqrt{-1}$ is an imaginary unit.

A key parameter derived from complex permittivity is the loss tangent, denoted as $\tan\delta$, which defines the material dielectric performance. It is defined as the ratio of the imaginary component to the real component of a material's complex permittivity [142].

$$\tan\delta = \frac{\epsilon''}{\epsilon'} \quad 3.2$$

This parameter measures a material's ability to convert electromagnetic energy into heat [143]. A higher loss tangent indicates greater dielectric loss, meaning the material is more efficient at transforming incoming electromagnetic wave energy into thermal energy. This energy dissipation is essential for effective microwave absorption, as it enables the energy to be absorbed and diminished within material rather than reflected back[21]. This characteristic enhances the overall performance of microwave absorber materials. In addition to dielectric behaviour, magnetic loss also influences absorption performance. Magnetic response is expressed through complex permeability, μ , which μ' indicates energy storage due to magnetic polarization and μ'' relates to magnetic loss. The magnetic loss tangent is expressed as:

$$\tan\delta = \mu''/\mu' \quad (3.3)$$

The attenuation constant α , which describes how rapidly the wave amplitude decays within a material, is another critical factor. It is derived from the material's dielectric and magnetic properties and is expressed [144]:

$$\alpha = A \times \frac{\omega}{c} \times \sqrt{\frac{\mu' \epsilon'}{2}} \times \sqrt{\left[\sqrt{1 + (\tan\delta)^2} - 1 \right]} \quad (3.4)$$

Here, ω is angular frequency $2\pi f$, c is speed of light, and A is a unit conversion factor (8.68/100). The attenuation constant quantifies how effectively the material can absorb microwave energy.

Power loss within the absorber is described by [5]:

$$A = \frac{1}{2} \sigma |E|^2 + \frac{1}{2} \omega \epsilon_0 \epsilon'' |E|^2 + \frac{1}{2} \mu_0 \mu'' |H|^2 \quad (3.5)$$

Here, E and H represent the magnitudes of electric and magnetic fields, respectively, while σ is electrical conductivity. The dielectric loss term ϵ'' and magnetic loss term μ'' indicates how energy from the EM wave is converted into heat.

Agricultural waste materials are mainly dielectric and contain negligible magnetic components. As a result, their magnetic permeability μ' is close to 1, and magnetic loss μ'' is nearly zero, indicating minimal magnetic contribution. Consequently, absorption is primarily governed by dielectric and conductive mechanisms, allowing Equation (3.6) to be simplified as [5]:

$$A = \frac{1}{2} \sigma |E|^2 + \frac{1}{2} \omega \epsilon_0 \epsilon'' |E|^2 \quad (3.6)$$

3.2.1 Polarization Mechanisms Behind Dielectric Behaviour

The dielectric behaviour of a material is crucial in determining its effectiveness as a microwave absorber. When exposed to an external electromagnetic field, dielectric materials undergo polarization, which is the internal rearrangement of charges. This process influences their ability to store and dissipate electric energy. The main polarization mechanisms that affect dielectric behaviour include electronic, ionic, dipolar, and interfacial (space charge) polarization. Each of these mechanisms contributes differently to the performance of microwave absorption. These principles are depicted in Figure 3.2.

3.2.1.1 Electronic polarization

Electronic polarization is the fastest form of polarization that occurs in dielectric materials. This occurs when an external electric field is applied, causing a small displacement of the negatively charged electron cloud relative to the positively charged nucleus within atoms or

molecules. [146]. This displacement creates an induced dipole moment. Because electrons have low mass, this type of polarization responds almost instantaneously to the applied field, making it highly effective at very high frequencies.

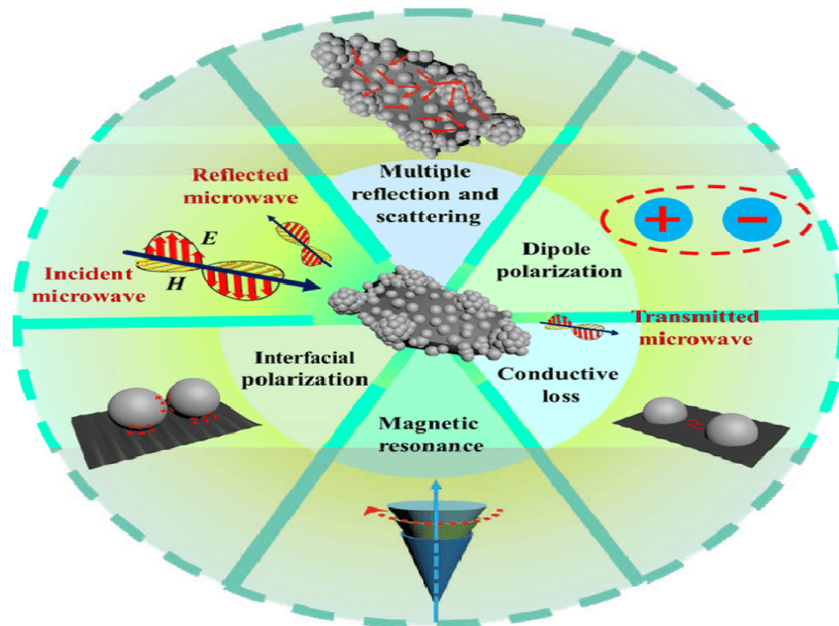


Figure 3.2 Schematic Representation of the electromagnetic wave Absorption Mechanism in a Dielectric Microwave Absorber[145]

While electronic polarization has a relatively minor direct contribution to microwave absorption at lower frequencies, it significantly influences the real part of complex permittivity ϵ' . This influence affects the overall dielectric behaviour of the material. However, electronic polarization has less of an impact on the imaginary part of permittivity ϵ'' , which is more directly responsible for energy dissipation. In composite microwave absorber materials, electronic polarization plays a supportive role by enhancing the dielectric constant. It complements slower polarization mechanisms, such as dipolar and interfacial polarization, which are more active in the microwave frequency range and primarily responsible for dielectric loss.

3.2.1.2 Ionic polarization

This type of polarization occurs in materials with ionic bonds, where the application of an electric field causes positive and negative ions to shift in opposite directions, forming dipoles [147]. This displacement contributes to both the storage and dissipation of electric energy. Ionic polarization is particularly effective in the infrared and lower microwave frequency ranges and plays a moderate role in dielectric loss. This is especially for biowaste materials that contain naturally occurring mineral ions or ionizable functional groups.

3.2.1.3 Dipolar polarization

42 A significant contributor to microwave absorption is dipolar or orientational polarization, which occurs in molecules that have permanent dipole moments. When these molecules are exposed to an alternating electric field, they attempt to align themselves with the direction of the field. However, due to their rotational inertia and the frequency of oscillation, they cannot perfectly follow the field, resulting in a delay. This delay causes energy to be dissipated in the form of heat, making dipolar polarization a major factor in enhancing the imaginary permittivity ϵ'' . This phenomenon is directly responsible for dielectric loss and microwave attenuation. Biowaste-derived materials are generally abundant in polar functional groups, like hydroxyl and carboxyl groups, which promote dipolar polarization under microwave radiation [147].

3.2.1.4 Interfacial polarization

The most significant mechanism in heterogeneous composite systems, particularly those that combine biowaste with conductive additives like charcoal, graphene, carbon nanotubes (CNTs), is interfacial or space charge polarization. This polarization arises at the interfaces between materials with different electrical conductivities and dielectric constants. When an electric field is applied, mobile charges accumulate at these boundaries, creating localized dipoles and enhancing dielectric loss. While interfacial polarization is most significant at low to intermediate frequencies, it also contributes importantly across the microwave range in composite absorbers [148]. In biowaste and conductive material composites, the contrast between the conductive carbon nanotubes and the insulating organic matrix leads to strong interfacial polarization. This results in higher values of ϵ'' , enhancing the absorption of electromagnetic energy.

18 Among these different types of polarization, dipolar and interfacial polarization mechanisms play a crucial role in defining the dielectric properties of MAMs, particularly within the microwave range [120]. While electronic and ionic polarization mainly influence the real part of permittivity, they contribute less to dielectric loss. In contrast, dipolar polarization is caused by the significant frequency-dependent lag in dipole alignment and interfacial polarization resulting from charge accumulation at heterogeneous interfaces. Both enhance the imaginary component of permittivity. This enhancement is crucial for energy dissipation and microwave absorption. Therefore, when designing efficient microwave absorbers, particularly those using biowaste-based composites, it is essential to promote dipolar and interfacial polarization. This approach will help achieve high dielectric losses and broadband absorption characteristics.

3.3 Microwave Absorption Mechanism

When an electromagnetic wave reaches the interface between two media, such as air and an absorber, part of the wave is reflected, part is absorbed, and the remainder is transmitted into the material, as expressed in Equation (3.7) [149]:

$$P_i = P_r + P_a + P_t \quad (3.7)$$

where P_i incident power is P_t transmitted wave, and P_a is absorption power, for an ideal absorber P_r and P_t should be minimized, and P_a should be maximized.

Microwave absorption behaviour is primarily determined using scattering parameters S_{11} & S_{21} , where S_{11} denotes reflection at the material surface, and S_{21} refers to transmission through the material. The absorption rate (AR) is calculated by Equation (3.8) shown in Figure 3.3 (a).

$$AR(\omega) = 1 - |S_{11}|^2 - |S_{21}|^2 \quad (3.8)$$

In this chapter, all measurements were conducted using a configuration backed by a perfect electric conductor (PEC). The PEC backing was applied to one side of the material to completely eliminate transmission ($S_{21} = 0$), ensuring that the incident electromagnetic wave undergoes only reflection and absorption. Under these conditions, microwave absorption can be simplified and calculated exclusively from the reflection coefficient (S_{11}), as expressed in Equation (3.9), also shown in Figure 3.3(b).

$$AR(\omega) = 1 - R = 1 - |S_{11}|^2 \quad (3.9)$$

This approach allows accurate evaluation of the absorber's performance without considering transmission losses.

Reflection Loss (RL), expressed in decibels (dB), serves as a key parameter for assessing the microwave absorption capability of a material. It quantifies the portion of incident EM wave energy that is reflected from the air-absorber interface. The mathematical expression for RL is given in Equation (3.10) [56,150]:

$$RL = 20 \log \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right| \quad (3.10)$$

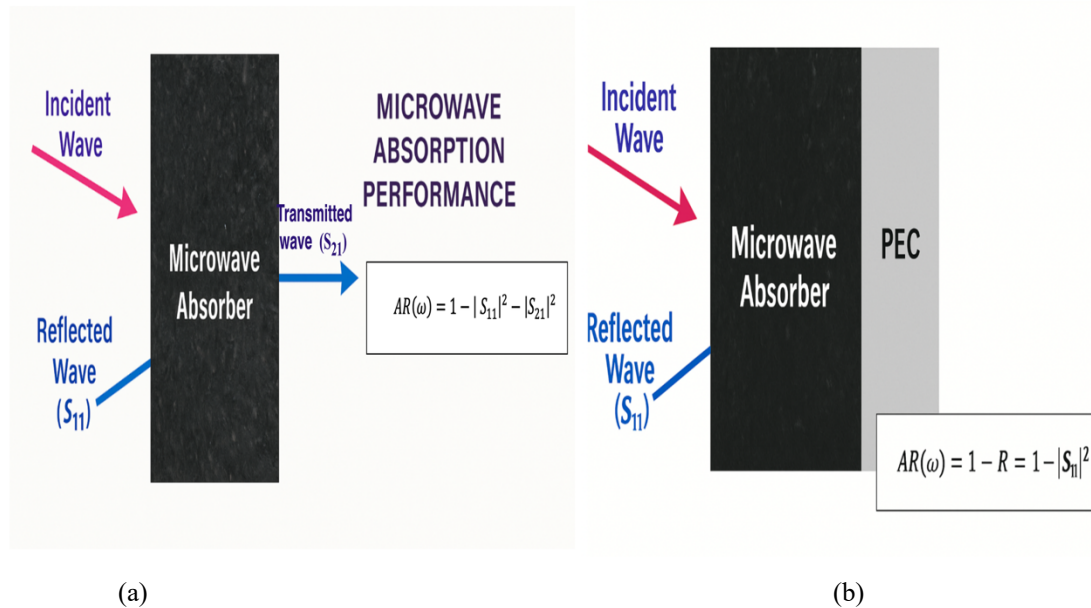


Figure 3.3 Schematic representation of microwave absorption measurement (a) without PEC backing showing reflection and transmission. (b) With PEC backing, it is possible to eliminate transmission and enable absorption calculation solely from reflection.

Z_{in} is input impedance of absorber, Z_0 is intrinsic impedance of free space ($Z_0=377\Omega$). The value of RL at 10 dB generally indicates the threshold for effective absorption. This indicates that the material absorbs at least 90% of the incoming electromagnetic energy, reflecting only about 10% [151]. When RL is less than or equal to -20 dB, it corresponds to 99% absorption, indicating excellent attenuation performance.

3.3.1 Fundamentals of Input Impedance and Impedance Matching

The efficiency of microwave absorption in a material is largely determined by how well its impedance matches that of free space [152]. For optimal absorption, the input impedance of the absorber (Z_{in}) should closely align with intrinsic impedance of free space ($Z_0=377$ ohms) [22]. When the input impedance (Z_{in}) is equal to characteristic impedance (Z_0), conductive loss mechanisms are minimized [153]. Conversely, poor impedance matching ($Z_{in} \neq Z_0$) causes strong reflections, which reduce the overall absorption efficiency. In this chapter, all measurements were conducted using a perfect electric conductor (PEC) backing to eliminate transmission, ensuring that the incident electromagnetic wave undergoes only reflection and absorption. Under this configuration, the total absorption rate is simplified by equation (3.10). The reflection coefficient, denoted as Γ , is defined by the formula [5]:

$$\Gamma = \frac{Z_m - Z_0}{Z_m + Z_0} \quad (3.10)$$

If the impedance of the material (Z_m) perfectly matches the free space impedance (Z_0), the reflection coefficient becomes zero. This indicates that there is no reflection and that electromagnetic energy is completely transmitted into the absorber. This condition is met when the normalized impedance fulfils the following equation (3.11) [147]:

$$\frac{Z_m}{Z_0} = \sqrt{\frac{\mu_r}{\epsilon_r}} = 1 \quad (3.11)$$

The Input impedance of the absorber is mathematically expressed by equation (3.12) [10]:

$$Z_{in} = Z_0 \sqrt{\frac{\mu_r}{\epsilon_r}} \tanh \left[j \frac{2\pi f d}{c} \sqrt{(\mu_r \epsilon_r)} \right] \quad (3.12)$$

Where f is frequency of the incident wave, d is absorber thickness, c is speed of light, and j is the imaginary unit. For microwave absorbers made from biowaste, the materials are typically non-magnetic, so their relative permeability is considered $\mu_r = 1$. In these cases, microwave absorption mainly relies on dielectric losses caused by dipolar and interfacial polarization, along with conductive loss mechanisms. Effective impedance matching can be achieved by carefully adjusting the complex permittivity and optimizing the thickness of the absorber. This allows for maximum penetration of electromagnetic (EM) energy and efficient attenuation within the material.

This principle is fundamental in designing efficient microwave absorber materials, particularly those made from biocomposites. By tailoring the dielectric and magnetic properties, it is possible to adjust the impedance to match that of free space

3.3.2 Absorbed Power Estimation

When an electromagnetic wave strikes a microwave absorber backed by a metallic plate or perfect electric conductor (PEC), transmission through the material is completely suppressed. The incident energy is then divided into two components: reflection and absorption. The absorbed power percentage can be estimated from the reflected power, as no transmission occurs in this configuration. The percentage of absorbed energy is calculated by using in equation (3.13) [10]:

$$\text{Absorption \%} = 100 - \text{Reflected power} = \left[100 - 100 * \left(10^{(-RL/10)} \right) \right] \quad (3.13)$$

The reflected power is expressed in decibels. A higher absorption percentage indicates better microwave attenuation. For example, if the calculated absorption exceeds 90%, the material is deemed an effective microwave absorber. Absorption levels above 99% signify excellent

attenuation performance. This simplified approach is very effective for evaluating absorber efficiency in PEC-backed configurations because it connects the absorbed power to the reflected energy, thereby removing the need to consider transmission losses.

3.4 Conductivity and Conduction Loss Mechanisms in Microwave Absorbers

Electrical conduction is one of the key mechanisms responsible for microwave energy loss in absorbing materials. This process depends on how charge carriers behave within the material's grain boundaries. In agricultural-based microwave absorbers, which are typically non-magnetic (i.e., $\mu'' = 0$), the main factors contributing to wave absorption are dielectric loss and conduction loss [154].

The overall conductivity of the material consists of both dc and ac components, expressed by the following equation (3,14):

$$\sigma_{ac} = A(2\pi f)^2 + \sigma_{dc} \quad (3.14)$$

where A represents the pre-exponential factor or characteristic factor, f denotes the frequency, and σ_{ac} is generally associated with hopping conduction and ac conductivity [10]. The term s , which ranges from 0 to 1, corresponds to the frequency component. Its values span from 0 for ideal ionic-type crystals to 1 for ideal Debye dielectric dipolar-type crystals. At low frequencies, direct current conductivity σ_{dc} dominates, and conduction occurs due to the movement of charges influenced by the electric field. These charges encounter resistance, leading to heat generation from collisions, a phenomenon known as conduction loss. As the frequency increases, the alternating current (AC) component becomes significant, resulting in hopping conduction, where charge carriers jump between localized sites.

The relationship between conductivity and permittivity can also be represented using complex notation.

$$\sigma = j\omega\epsilon_0\epsilon = \sigma' + j\sigma'' = j\omega\epsilon_0(\epsilon' - j\epsilon'') \quad (3.15)$$

From this, the real part of conductivity (σ') and the imaginary part (σ'') can be expressed as:

$$\sigma' = \omega\epsilon_0\epsilon'' = 2\pi f\epsilon_0\epsilon' \tan\delta \quad (3.16)$$

$$\sigma'' = \omega\epsilon_0\epsilon' \quad (3.17)$$

Where, ω is angular frequency, ϵ_0 is permittivity of free space, ϵ' is real part of permittivity, ϵ'' is the imaginary part of permittivity and $\tan\delta$ is tangent loss [155]. These expressions clearly illustrate how conductivity increases with frequency, especially in the high-frequency range, due to the enhanced movement of charge carriers [5]. Since magnetic loss is typically absent in most biowaste-based absorbers, the energy dissipation within the material primarily

results from conduction and dielectric losses. This can be expressed using the simplified equation (3.18) for energy loss [5]:

$$A = \frac{1}{2} \sigma |E|^2 + \frac{1}{2} \omega \epsilon_0 \epsilon'' |E|^2 \quad (3.18)$$

This formula indicates that the total energy loss results from two mechanisms: conduction loss (first term) and dielectric loss (second term). Here, $|E|$ signifies magnitude of the electric field [156]. Together, these mechanisms convert absorbed electromagnetic wave energy into heat. This conversion is essential for the effectiveness of microwave-absorbing materials, particularly those made from bio-waste-based materials.

3.5 Impact of Thickness Variation on Microwave Absorbing Properties

The thickness of an MA must be selected with care to minimize the reflection of incident waves. The absorber thickness, denoted as t_m , is typically chosen as an odd multiple of one-quarter of the wavelength within material, as shown in Equation (3.19) [10].

$$t_m = \frac{n\lambda_m}{4} \quad (3.19)$$

In this context, $n = 1$ it indicates the first absorption minimum at the lowest frequency of interest. The wavelength λ_m within the absorber is related to free-space wavelength λ_0 through the material's dielectric properties, as expressed in equation (3.20).

$$\lambda_m = \frac{\lambda_0}{4\sqrt{|\epsilon_r|}} \quad (3.20)$$

ϵ_r is the complex relative permittivity, assuming the material is non-magnetic, so $\mu_r = 1$. Substituting this into equation (3.21) yields:

$$t_m = \frac{n\lambda_0}{4\sqrt{|\epsilon_r|}} \quad (3.21)$$

When the calculated thickness t_m , matches the thickness at which the strongest absorption dip appears experimentally, it confirms that the absorber adheres to the classic quarter-wavelength matching principle.

3.6 Impact of Particle Size Variation on Microwave Absorbing Properties

The particle size of a material significantly influences its microwave absorption performance. Smaller particle sizes lead to a higher surface area and a greater number of surface atoms [157]. This configuration promotes increased internal reflections of incident electromagnetic waves. These multiple reflections intensify the interaction between the EM wave and the material, resulting in increased dielectric constant and dielectric loss [10,158]. This behaviour is characterized by the complex permittivity, $\epsilon = \epsilon' - j\epsilon''$, where ϵ' denotes energy storage and ϵ'' signifies energy dissipation. Small particle sizes also enhance interfacial polarization and conduction losses, which further increases microwave attenuation. The attenuation capability

4 is quantitatively represented by the attenuation constant, given by the formula: $\alpha = \sqrt{\pi f \mu \epsilon''}$ where μ is magnetic permeability, ϵ'' is dielectric loss, and f is frequency. As a result, the combined impact of improved dielectric properties and interfacial polarization due to smaller particle size greatly enhances the overall microwave absorption properties of the material.

In this chapter, the properties of microwave absorption relevant to MAMs are discussed in detail to understand their contributions to overall absorption performance. All essential properties of MAMs have been thoroughly explained to clarify their role in determining absorption behaviour. Utilizing these fundamental properties, the microwave absorption characteristics of agricultural waste and carbon nanotubes (CNTs) have been analyzed in detail. The study emphasizes that the absorption characteristics of materials derived from biowaste are primarily influenced by dielectric loss mechanisms, as they exhibit negligible or absent magnetic properties.

3.7 Analysis of Microwave Absorption Properties of Agricultural Waste and CNT Materials

Agricultural residues are generated in large quantities worldwide as a byproduct of farming activities. These materials are often discarded in open fields or directly burned to clear land for the next cultivation cycle. While open-field burning is a practical method for farmers, it emits large quantities of particulate matter, greenhouse gases, and other harmful pollutants, leading to air pollution, environmental damage, and health risks for surrounding populations [14]. Such unsustainable disposal practices highlight the need to develop environmentally friendly and value-added applications for these residues.

In recent years, researchers have explored alternative uses for agricultural waste, one of the most promising being its application in fabricating microwave absorber materials. Unlike conventional disposal, this approach helps manage waste and offers potential for developing lightweight, low-cost, and eco-friendly materials suitable for EMI shielding. The suitability of agricultural residues for microwave absorption can be attributed to their inherent dielectric properties, primarily due to their natural carbon content.

Carbon is a critical factor influencing the dielectric loss properties of materials in MA. Due to the lignocellulose nature of plant-based matter, agricultural wastes naturally contain large levels of carbon. Carbon-rich materials promote dielectric loss through mechanisms such as interfacial polarization, dipole relaxation, and conduction loss when exposed to an

electromagnetic field [159]. These procedures make it easier for incident microwave energy to be converted into heat, which attenuates electromagnetic waves.

3.7.1 Selection of Agricultural Waste Materials and CHNS Analysis

Three different types of agricultural waste were chosen for analysis of their dielectric properties in this study.

The selection was guided by three main criteria: (i) local availability in large quantities, (ii) ease of collection and disposal without the need for extra processing and (iii) inherent carbon content that can contribute to EM wave attenuation. Sugarcane bagasse (SG), dried banana leaves (DBL), and teak wood sawdust (TWS) were selected as representative agricultural wastes for MAMs development due to their availability and inherent carbon content. Sugarcane bagasse (SG), a fibrous residue obtained during sugar production is generated in substantial amounts. In many cases, it is either burned or disposed of in landfills, leading to environmental pollution. CHNS (Carbon, Hydrogen, Nitrogen, Sulphur) elemental analysis shows that SG contains about 37.34% carbon, making it a lightweight and porous carbon-rich material. These characteristics contribute significantly to enhancing dielectric loss, thereby improving its potential as a microwave absorbing material. Dried banana leaves (DBL) are collected after the banana plant completes its life cycle or when the leaves are cut during trimming. Instead of being thrown away, these waste leaves can be dried and processed. They contain about 42.34% carbon, which is useful for absorbing microwaves. Their rough, layered surface makes electromagnetic waves bounce and scatter inside the material many times, which improves the overall absorption. Teak wood sawdust (TWSD), which comes from cutting and processing teak wood, contains about 46.47% carbon, giving it good potential for dielectric applications. However, because it is not available in large quantities, it is less suitable for large-scale use. All three materials, SG, DBL, and TWSD have a high carbon content and are abundant in lignocellulose biomass, both of which are crucial for absorbing and lowering microwave radiation. The CHNS elemental analysis of these three materials was performed at the SAI laboratory facilities of Thapar Institute of Engineering and Technology (TIET), Patiala. The results revealed that all three types of agricultural waste contain a high percentage of carbon, ranging from 37.34%, 42.34% and 46.7%, respectively. The carbon-rich composition is vital for boosting MA performance, as it promotes dielectric loss mechanisms, including conduction loss and interfacial polarization [160]. The detailed elemental compositions are presented in Table 3.1, which served as the basis for selecting suitable materials for composite fabrication.

Table 3.1. CHNS Elemental analysis of agricultural waste materials

Elements	Percentage of elements		
	Sugarcane Bagasse	Dried Banana Leaves	Teak wood sawdust
Carbon	37.34%	42.34%	46.47%
Hydrogen	6.44%	5.47%	5.64%
Nitrogen	0.62%	0.56%	0.42%
Sulphur	-	-	-

These three Agricultural wastes are naturally rich in carbon but lack ferromagnetic components, making them non-magnetic with magnetic permeability values close to unity. This means their microwave absorption ability mainly comes from dielectric properties rather than magnetic losses.

In this proposed study, the agricultural wastes were first processed into powder form, then developed into different samples which suitable for X-band frequency testing. The fabrication process included drying, grinding, sieving, and mixing with other components to ensure uniformity. After fabrication, the samples were tested using a rectangular waveguide setup to measure dielectric properties such as dielectric constant and loss factor. These measurements help to understand how effectively the materials can weaken microwave signals through dielectric loss mechanisms like conduction loss and interfacial polarization. The aim of this study is to develop eco-friendly, low-cost, and efficient microwave absorbers from agricultural waste, reducing electronic interference while promoting sustainable waste management.

3.7.2 Fabrication Methodology for Agricultural Waste-Based Microwave Absorber

This proposed study aims to use three distinct agricultural waste materials to create microwave absorber samples and evaluate their dielectric properties. The fabrication process for these absorbers consists of a series of systematic steps, as shown in Figure 3.4, which outlines the overall methodology employed in this proposed study. Three types of agricultural waste were selected in their raw form: sugarcane bagasse (SG), dried banana leaves (DBL), and teak wood sawdust (TWSD). These raw materials were collected from local sources and underwent a drying process. The drying was conducted naturally under sunlight for one week to eliminate any moisture present in the biomass. This step is essential because excessive moisture can reduce grinding efficiency and may lead to agglomeration during further processing. Once completely dried, the raw agricultural wastes were reduced into smaller pieces and processed individually using a home-based grinder. Each material, SG, DBL, and TWSD, was ground separately to obtain powdered forms. However, grinding alone did not produce a uniform

powder with consistent particle sizes so therefore, the ground material was further refined through sieving. By using sieves with appropriate mesh sizes, the powder was enhanced to achieve a finer, more micro-structured form.

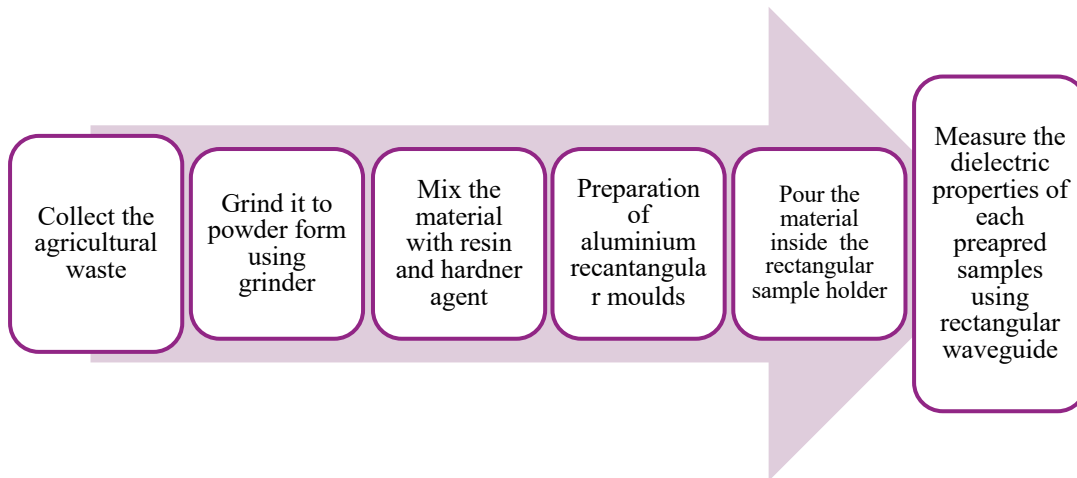


Figure 3.4 Steps for fabricating and testing microwave absorbers

This combined grinding and sieving approach resulted in three different powders: SG powder, DBL powder, and TWSD powder is shown in Figure 3.5. Each of these powders was then used for the fabrication of microwave absorber samples. After powder preparation, it was important to evaluate the particle size distribution of the agricultural waste powders, since particle size plays a major role in defining the dielectric properties of the prepared samples [162]. Therefore, the particle size analysis was conducted using an optical microscope equipped with a 50× magnification lens, as illustrated in Figure 3.6. This optical microscopic observation revealed that particle sizes of powders were non-uniform, which is typical for agricultural waste-based powders produced using grinding and sieving techniques. The particle size of SG exhibited sizes from 95 μm to 580 μm , DBL showed particles between 40 μm and 350 μm , and TWSD was found in the range of 130–450 μm . The non-uniformity arises because the powders were prepared by mechanical grinding followed by sieving, which does not produce highly controlled or uniform particle distributions. The powder's particle size is critical in determining how electromagnetic waves interact with the material's surface [147]. Smaller particles provide a more complex internal pore structure, higher surface area, and larger density of surface atoms, which in turn facilitate multiple internal reflections of incident microwaves and improve energy dissipation within the material.

After determining the particle size of all the prepared powders, the next step involved the fabrication of samples. The agricultural waste powder was mixed with polyester resin (PR) and methyl ethyl ketone peroxide (MEKP), which acted as a binding agent. In addition, a small quantity of cobalt accelerator was incorporated to promote the curing process [161]. The

mixture was then thoroughly stirred to ensure uniform dispersion of the agricultural waste powder within the resin system and to obtain a homogeneous composition. Once a consistent mixture was achieved, it was carefully poured into the aluminum rectangular mold with dimensions of 22.860 mm × 10.160 mm × 2.000 mm and left to cure at room temperature for 24 hours to attain complete hardening and structural stability. After curing, the solidified samples were removed from the mold, and three types of samples, SG, DBL, and TWSD, were prepared following the same fabrication procedure. The overall fabrication process is illustrated in Figure 3.7, while the three prepared samples are displayed in Figure 3.8. The preparation summary and physical description of the developed samples are described in Table 3.2.

Table 3.2. Preparation Summary and Physical Dimensions of Developed Samples

Samples	Amount of agricultural waste powder(gm)	Resin and hardener (gm)	Mould dimensions (mm)	Thickness of sample (mm)	Samples code
Sugarcane Bagasse	2	3	22.86×10.16	2	SG
Dried Banana Leaves	2	3	22.86×10.16	2	DBL
Teak wood saw dust	2	3	22.86×10.16	2	TWSD

After fabricating the samples, their dielectric properties were analyzed using the rectangular waveguide transmission line method within the X-band frequency range (8.2–12.4 GHz). The waveguide was calibrated using the Short, Open, Load, and Thru (SOLT) technique to ensure measurement accuracy [66]. Calibration was an essential step performed prior to testing to eliminate systematic and predictable errors caused by imperfections in the measurement system. The complete experimental setup for this procedure is illustrated in Figure 3.9. Each sample was precisely fabricated to match the internal dimensions of the waveguide, with measurements of $a = 22.86$ mm, $b = 10.16$ mm, and a thickness of 2 mm. These samples were then carefully inserted into the waveguide, and their dielectric constant and dielectric loss were recorded individually.

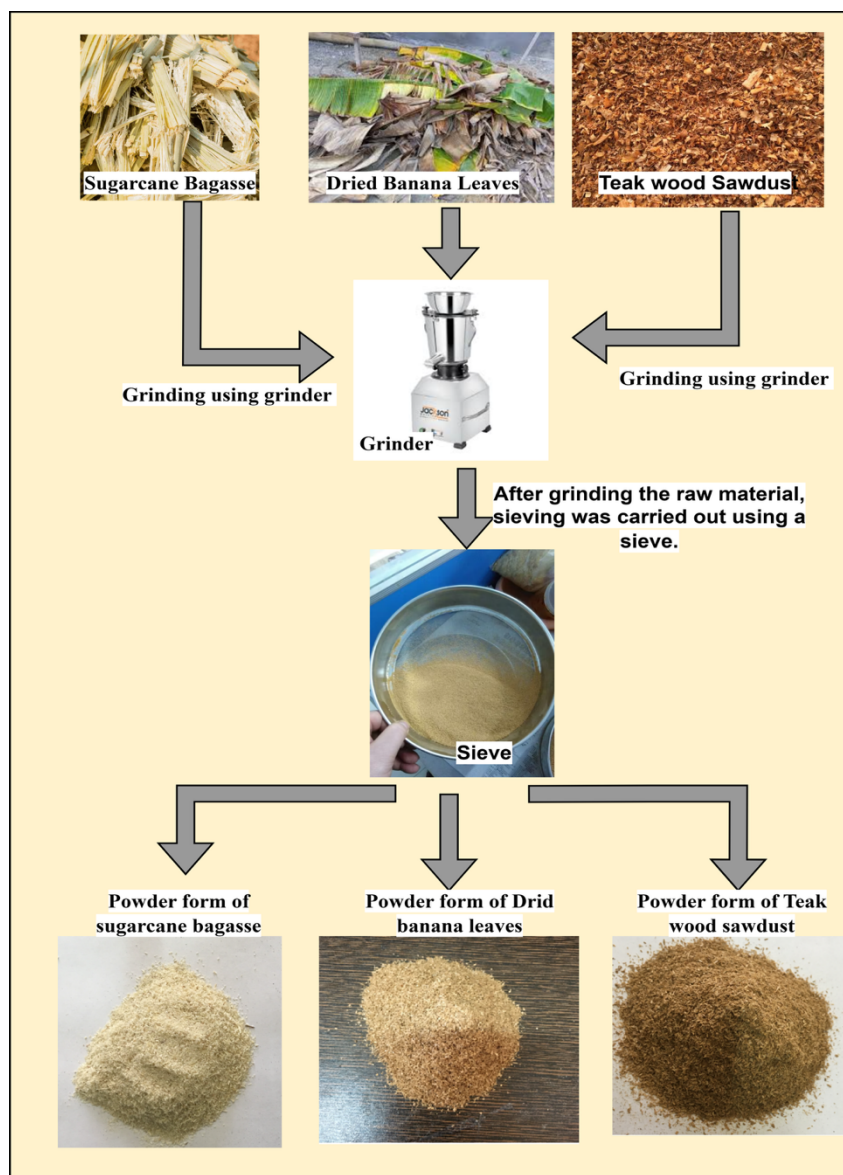


Figure 3.5. Process of Agricultural Waste Powders preparation through Drying, Grinding, and Sieving Process

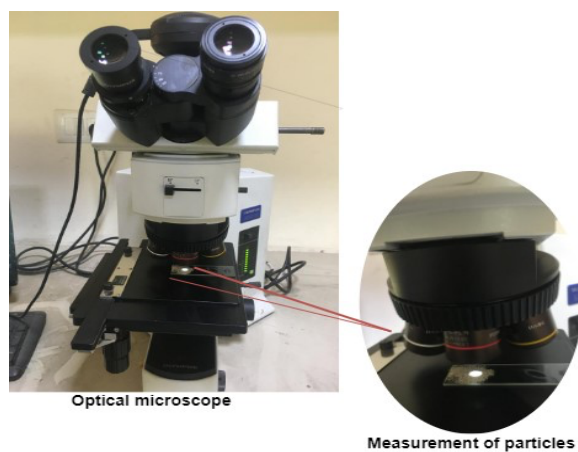
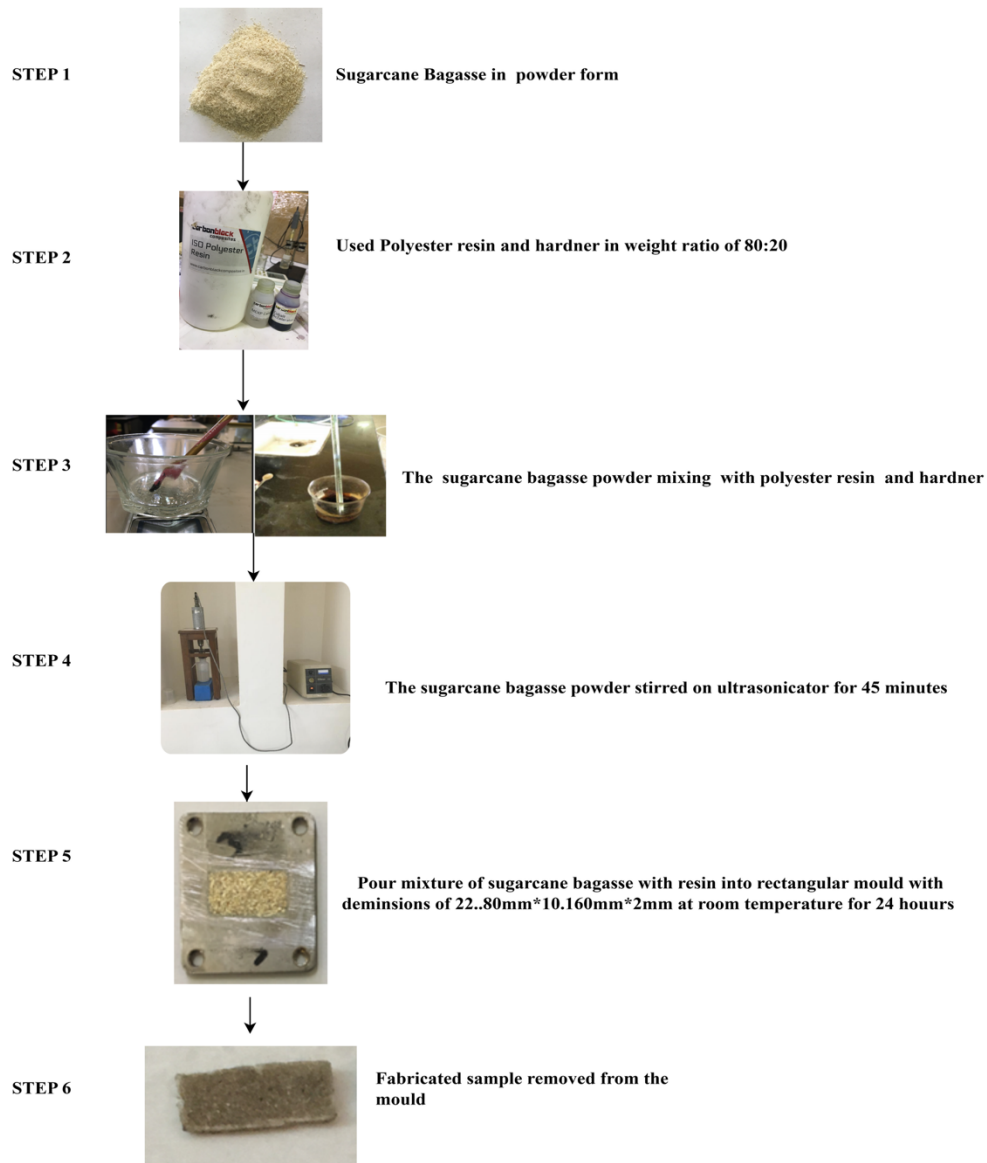


Figure 3.6. Optical Microscopic Examination Setup for Particle Size Analysis at 50× Magnification.



Fabrication process of agricultural waste microwave absorber sample prepration

Figure 3.7 Fabrication process of agricultural waste microwave absorber sample preparation



Figure 3.8 Developed microwave absorber samples using sugarcane bagasse, dried banana leaves, and teak wood sawdust

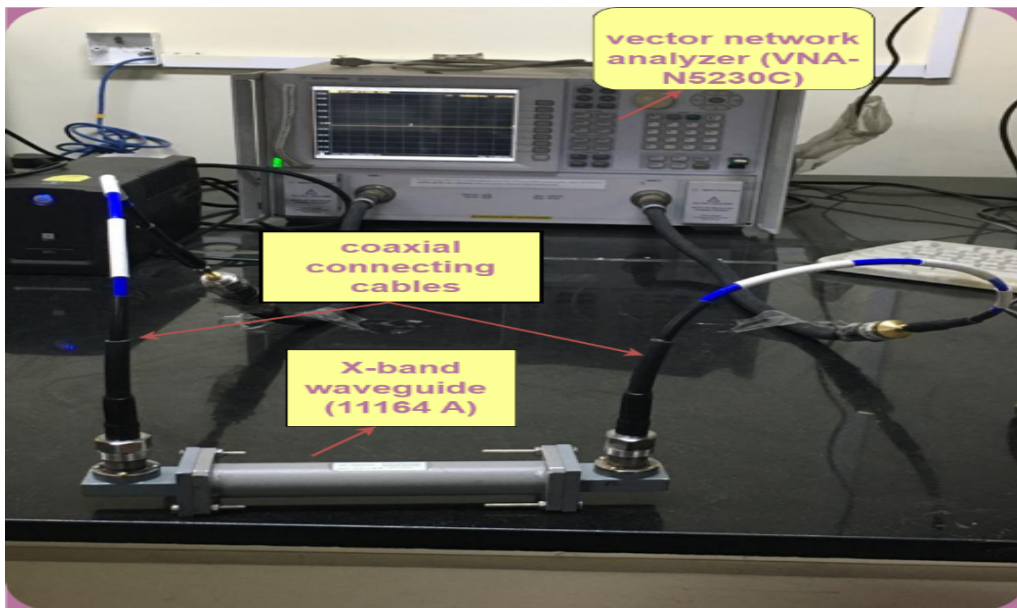


Figure 3.9 Experimental setup for measuring dielectric properties of developed samples

The measurements were performed using an X-band rectangular waveguide connected to a Vector Network Analyzer (VNA) through high-frequency coaxial cables. After obtaining the dielectric properties values, the results for the three fabricated samples were systematically compared with other biowaste-based microwave absorber materials reported in the literature.

3.7.3 Dielectric Characterization of Agricultural Waste Samples

The dielectric behaviour of a material is a critical parameter in determining its microwave absorption efficiency, as it reveals how effectively the material can store and transform incident electromagnetic energy into heat [10]. In this proposed study, dielectric properties of three fabricated samples: SG, DBL, and TWSD were investigated. All these materials are made of pure agricultural waste and behave as non-magnetic dielectric materials. Since they are non-magnetic in nature, their magnetic permeability (μ) is assumed to be equal to 1. Therefore, only the dielectric properties of these samples were considered for analysis. The dielectric properties of the prepared SG, DBL, and TWSD samples were individually analyzed using a VNA coupled with a WR-90 waveguide, operating within the X-band frequency range.

The dielectric behaviour of SG, DBL, and TWSD across the X-band, as shown in Tables 3.3 and 3.4, confirms that all three materials possess the dielectric characteristics required for effective microwave absorption applications. These properties include dielectric constant (ϵ'), dielectric loss (ϵ''), loss tangent ($\tan \delta$), and conductivity (σ), collectively defining a material's capacity to store, polarize, and dissipate EM energy [163].

Table 3.3 Dielectric constant (ϵ') of SG, DBL, and TWSD Across the X-Band Frequency Range

Sample Code	Material	Dielectric constant (ϵ') at X-band frequency				
		8	9	10	11	12
SG	Sugarcane Bagasse	2.07	2.05	2.02	1.99	1.76
DBL	Dried Banana Leaves	2.85	2.83	2.78	2.56	2.36
TWSD	Teak wood saw dust	3.11	3.07	3.06	3.06	3.02

Table 3.4 Dielectric LOSS ϵ'' of SG, DBL, and TWSD Across the X-Band Frequency Range

Sample Code	Material	Dielectric Loss (ϵ'') at X-band frequency				
		8	9	10	11	12
SG	Sugarcane Bagasse	0.20	0.17	0.15	0.12	0.10
DBL	Dried Banana Leaves	0.28	0.25	0.24	0.24	0.20
TWSD	Teak wood saw dust	0.30	0.29	0.28	0.26	0.25

Table 3.5. Tangent loss δ of SG, DBL, and TWSD Across the X-Band Frequency Range

Sample Code	Material	Tangent loss (δ) at X-band frequency				
		8	9	10	11	12
SG	Sugarcane Bagasse	0.098	0.085	0.076	0.064	0.058
DBL	Dried Banana Leaves	0.10	0.09	0.087	0.082	0.07
TWSD	Teak wood saw dust	0.098	0.092	0.088	0.086	0.083

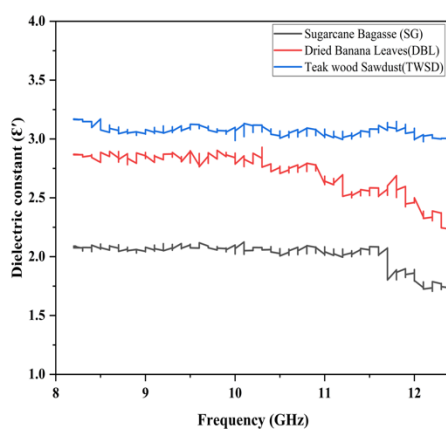
Table 3.6. Conductivity σ of SG, DBL, and TWSD Across the X-Band Frequency Range

Sample Code	Material	Conductivity (σ)s/m at X-band frequency				
		8	9	10	11	12
SG	Sugarcane Bagasse	0.102	0.088	0.078	0.064	0.051
DBL	Dried Banana Leaves	0.143	0.129	0.121	0.112	0.103
TWSD	Teak wood saw dust	0.166	0.162	0.153	0.147	0.139

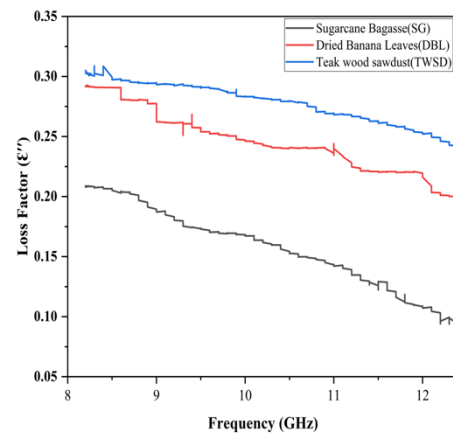
The dielectric constant (ϵ') of all three samples gradually decreases with increasing frequency [66]. This behaviour arises from relaxation phenomena, where at higher frequencies, dipolar polarization lags behind the rapidly oscillating electric field, leading to a decrease in dielectric storage capacity. Among the three materials, TWSD demonstrates the highest average dielectric constant ($\epsilon' = 3.07$), while DBL and SG exhibit moderate values of 2.71 and 2.02, respectively. The moderate dielectric constant (ϵ') values of SG and DBL show effective impedance matching, which is crucial for minimizing reflection loss and allowing maximum microwave penetration. Proper impedance matching ensures that incident electromagnetic waves enter the material efficiently instead of being reflected at the air-material interface [164]. Similarly, the dielectric loss (ϵ''), which characterizes the ability of a material to dissipate electromagnetic energy in the form of heat, shows that TWSD exhibits the highest average dielectric loss of approximately 0.28. In comparison, DBL and SG demonstrate considerable dielectric loss values of 0.24 and 0.20, respectively. These values confirm that both DBL and SG are capable of absorbing and converting a significant portion of the incident electromagnetic energy into thermal energy, a fundamental requirement for efficient microwave absorption. The loss tangent ($\tan \delta$) and conductivity (σ) of SG and DBL are found to be in a comparable range with TWSD, highlighting their potential for energy dissipation through both dielectric relaxation and conduction mechanisms. Although TWSD exhibits slightly superior dielectric and conductivity values, the performance of SG and DBL remains significant.

The comparative analysis of the dielectric properties of Sugarcane Bagasse (SG), Dried Banana Leaves (DBL), and Teak Wood Sawdust (TWSD) presented in Figure 3.8 (a–e) Figure (a) shows that the dielectric constant (ϵ') is highest for TWSD, followed by DBL and SG, indicating a greater ability of TWSD to store electromagnetic energy. Figure (b) depicts the loss factor (ϵ''), which reflects energy dissipation within the material, and again TWSD exhibits the highest value, followed by DBL and SG, with all materials showing a slight decreasing trend with frequency. Figure (c) illustrates the loss tangent ($\tan \delta$), where DBL shows slightly higher values than TWSD at lower frequencies, indicating strong dielectric relaxation behavior, while SG remains the lowest. Figure (d) presents the electrical conductivity (σ), with TWSD demonstrating superior conductivity compared to DBL and SG, suggesting enhanced conduction loss. Overall, these results indicate that while TWSD exhibits marginally better dielectric and conductive performance, SG and DBL also maintain significant dielectric properties, making them promising candidates for microwave absorber applications. After

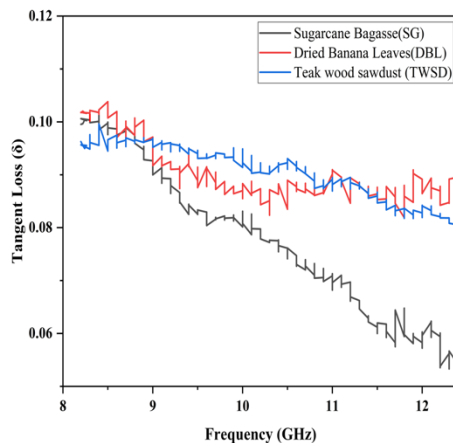
analyzing the dielectric properties of all three samples (SG, DBL, and TWSD). It is evident that these agricultural waste-based materials exhibit dielectric characteristics essential for microwave absorption applications. Their ability to store electromagnetic energy (through dielectric constant), dissipate energy as heat (through dielectric loss), and maintain impedance matching makes them suitable candidates for microwave absorber development. The inherent dielectric properties of these materials confirm that they can be effectively utilized as base materials for fabricating microwave absorbers.



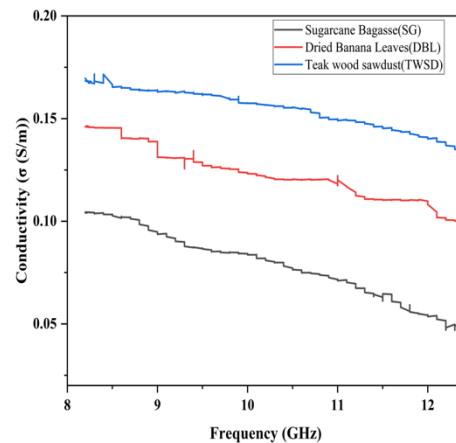
(a)



(b)



(c)



(d)

Figure 3.10 Comparison of dielectric characteristics between SG, DBL, and Teak wood saw dust (TWSD) (a) the dielectric constant, (b) loss factor, (c) loss tangent, (d) conductivity, and (e) conductivity loss.

Table 3.7 displays average dielectric characteristics of the three developed samples, SG,DBL and TWSDThe formula for calculating average dielectric properties is presented in Equation (3.22).

$$AVERAGE\ VALUE = \frac{\Sigma(f_{8.200} + \dots + f_{12.400})}{N} \quad (3.22)$$

N is a numerical value that corresponds to a floating-point frequency within the range of X-band.

Table 3.7. Average values of dielectric characteristics of SG ,DBL and TWSD samples for X-band.

Parameters	Samples		
	SG	DBL	TWSD
ε'	2.02	2.71	3.07
ε''	0.2	0.24	0.28
$\tan \delta$	0.07	0.09	0.09
σ'	0.07	0.12	0.15

The experimental results conclude that all three agricultural waste materials, Sugarcane Bagasse (SG), Dried Banana Leaves (DBL), and Teak Wood Sawdust (TWSD), possess measurable dielectric properties, including dielectric constant, dielectric loss, loss tangent, and conductivity, which are essential for electromagnetic energy attenuation. These characteristics confirm their potential as base materials for microwave absorber applications. Although TWSD demonstrates slightly higher dielectric and conductive performance compared to SG and DBL, its limited availability and difficulty in sourcing make it less practical for large-scale. In contrast, DBL and SG are more readily available, cost-effective, and sustainable, making them better candidates for further investigation. Therefore, for practical applications and reproducibility, DBL and SG materials are prioritized over TWSD.

After analyzing the dielectric properties of SG and DBL it was found that these materials exhibit moderate dielectric constants and loss factors, indicating their capability for electromagnetic energy attenuation through polarization mechanisms. However, their relatively low electrical conductivity limits their microwave absorption performance, particularly in terms of conduction loss. To overcome this limitation and enhance the absorption capability, the integration of highly conductive nanofillers becomes essential. CNTs are chosen for this purpose because they possess exceptionally high dielectric properties, superior electrical conductivity, and a unique one-dimensional nanostructure, which enables effective electron transport and multiple polarization mechanisms.

3.7.4 Dielectric Characterization of Carbon Nanotube

Carbon Nanotubes (CNTs) are one-dimensional nanostructures composed of rolled-up graphene sheets forming cylindrical tubes [165]. They exist in two main forms: Single-Walled Carbon Nanotubes (SWCNTs) and Multi-Walled Carbon Nanotubes (MWCNTs)[166]. In this study, MWCNTs were selected for incorporation into microwave absorber composites due to their greater availability, lower cost, and suitability for large-scale applications. Their multi-layered structure facilitates uniform dispersion within the polymer matrix, ensuring consistent composite performance. As shown in Table 3.8, MWCNTs exhibit efficient dielectric and conductive behaviour, promoting interfacial polarization and enhanced dielectric loss, which improves microwave absorption. These properties, along with practical advantages, make MWCNTs a preferred choice for effective electromagnetic wave attenuation in microwave absorber materials.

Table 3.8 Dielectric properties of Multi-walled Carbon nanotubes (MWCNTs) in the X-band

Parameters	Typical Range for MWCNTs
ϵ'	10-15
ϵ''	6-8
$\tan \delta$	0.6-0.8
σ'	10^3 - 10^4 S/m

A high dielectric constant (ϵ') ranging from 10 to 15 indicates that MWCNTs possess excellent capability to store electromagnetic energy through polarization mechanisms. The dielectric loss (ϵ'') between 6 and 8, along with a loss tangent ($\tan \delta$) of 0.6-0.8, reflects strong energy dissipation capability, meaning that absorbed EM energy is efficiently converted into heat through dipolar relaxation and interfacial polarization processes. Additionally, the electrical conductivity in the range of 10^3 – 10^4 S/m introduces substantial conduction loss, which is one of the dominant attenuation mechanisms in CNT-based composites.

These combined properties, high permittivity, strong dielectric loss, and superior conductivity, make MWCNTs an ideal additive for enhancing the microwave absorption performance of agricultural waste-based composites. Their presence not only improves dielectric characteristics but also ensures better impedance matching, leading to minimized reflection and maximized absorption of incident electromagnetic waves.

3.8 Summary and Contribution of the Chapter

8 In this chapter, the microwave absorption properties of absorber materials are discussed in
4 detail to clarify the mechanisms that govern EM wave attenuation. Key fundamental properties
such as dielectric constant, dielectric loss, electrical conductivity, impedance matching, and
attenuation mechanisms, including dipolar polarization, interfacial polarization, and
conductive loss, were thoroughly explained to highlight their roles in effective microwave
absorption. Special emphasis was placed on the fact that biowaste-derived materials primarily
exhibit dielectric loss due to their non-magnetic nature ($\mu_r = 1$). This makes their dielectric
properties the key factor in absorption performance.

Building on this theoretical foundation, the dielectric properties of three agricultural waste-
based materials (Sugarcane Bagasse (SG), Dried Banana Leaves (DBL), and Teak Wood
4 Sawdust (TWSD) were experimentally analyzed in the X-band frequency range (8.2–12.4
GHz). Although TWSD demonstrates slightly higher dielectric and conductive performance
compared to SG and DBL, its limited availability and difficulty in sourcing make it less
practical for large-scale. In contrast, DBL and SG materials are chosen for further study to
make composite MAMs, because more readily available, cost-effective, and sustainable,
making them better candidates.

6 To overcome this drawback, Multi-Walled Carbon Nanotubes (MWCNTs) were introduced as
conductive nanofillers due to their exceptional dielectric properties, superior electrical
conductivity, high aspect ratio, and ability to promote multiple polarization mechanisms. The
incorporation of MWCNTs significantly improved dielectric loss, conduction loss, and
impedance matching, enabling the development of high-performance, lightweight, and eco-
friendly biomass–CNT composite absorbers. This integration successfully addresses the
limitations of pure agricultural waste while reducing cost and weight compared to traditional
carbon-based absorbers.

65 The contribution of this chapter lies in establishing the potential of agricultural waste materials
as a sustainable base for microwave absorbers and demonstrating the critical role of CNTs in
enhancing their performance. This forms the foundation for developing next-generation EMI
shielding solutions and stealth technologies that are cost-effective, environmentally friendly,
and efficient across the X-band frequency range.

PUBLISHED WORK RELATED TO THIS CHAPTER:

1. Anju Tripathi and Karmjit Singh Sandha, “Eco-Friendly Organic Waste and CNT Composite for EMI Shielding Across X-Band: Applications in Cloud Servers and IoT Hardware,” International Conference on Next-Generation Cloud Innovations.
(Accepted)

CHAPTER 4

MICROWAVE ABSORPTION PERFORMANCE OF DRIED BANANA LEAVES/MWCNT COMPOSITE MATERIALS

In this chapter, an innovative bio-composite microwave absorber was fabricated by incorporating multi-walled carbon nanotubes (MWCNTs) into powdered dried banana leaves (DBL). The primary objective was to investigate and evaluate the EM wave absorption capability of DBL-MWCNT composite. The preparation involved a series of steps, including grinding, sieving, and ultrasonic treatment to ensure uniform dispersion and optimized mixing ratios of MWCNTs within the DBL matrix. The electromagnetic characteristics of the samples were evaluated using a rectangular waveguide setup in conjunction with a Vector Network Analyzer across the X-band frequency range. The impact of varying thicknesses and different filler concentrations of MWCNTs on reflection loss (RL) was thoroughly examined. Additionally, the experimental data were correlated with theoretical predictions to analyze the composite's behaviour under diverse electromagnetic conditions. This work contributes to the growing research on sustainable microwave absorbers by demonstrating how agricultural residues like banana leaves, when combined with nanomaterials, can offer a low-cost, environmentally responsible alternative to traditional microwave-absorbing substances.

4.1. Introduction

Agricultural waste materials have recently attracted considerable attention for their potential use in microwave absorber materials (MAMs). These materials are eco-friendly, lightweight, biodegradable, and readily available at a low cost. Among the available biowaste materials, DBL were selected as the primary material for this study because of their high carbon content, which is crucial for efficient microwave absorption [4].

Banana leaves are often considered agricultural waste, typically discarded or burned for disposal. This practice contributes to environmental pollution and deteriorates air quality. Utilizing banana leaves as a microwave absorber can not only offer an alternative to burning but also add value to this otherwise discarded resource. Dried banana leaves are suitable for this purpose due to their naturally high carbon content, which is crucial for enhancing dielectric loss and improving electromagnetic wave attenuation.

The carbon content of dried banana leaves was analyzed using a CHNS elemental analyzer, which measures the percentage of carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) in the

material [25]. As summarized in Table 4.1, dried banana leaves contain approximately 42.34% carbon, 5.47% hydrogen, and 0.56% nitrogen, while sulphur content is negligible. This relatively high carbon percentage highlights the significant potential of dried banana leaves as a base material for developing biowaste-derived microwave absorbers.

Table 4.1. CHNS Elemental Composition of Dried Banana Leaves

Elements	Dried banana leaves
Carbon (C)	42.34%
Hydrogen (H)	5.47%
Nitrogen (N)	0.56%
Sulphur (S)	-

The natural carbon content of DBL makes it effective as a microwave absorber. However, further improvements in absorption efficiency can be achieved by increasing its carbon content and optimizing its dielectric and magnetic properties. To enhance these characteristics, multi-walled carbon nanotubes (MWCNTs) were incorporated into the DBL matrix in varying weight percentages. MWCNTs are composed almost entirely of carbon and are renowned for their excellent electrical conductivity, high aspect ratio, and superior dielectric loss properties. Their addition not only increases the overall carbon content of the composite but also improves impedance matching, dipole polarization, and charge mobility, crucial factors for achieving superior microwave attenuation.

This chapter provides motivation for the use of biowaste-derived materials to develop MAMs. Dried banana leaves (DBL) were chosen as the base material due to their naturally high carbon content, which is essential for effective microwave absorption. To improve absorption efficiency further, multi-walled carbon nanotubes (MWCNTs) were added in varying weight percentages and blended with powdered DBL to create DBL-MWCNT composite samples. The microwave absorption properties of both pure DBL and DBL-MWCNT composites were evaluated in the X-band frequency range by measuring key parameters such as dielectric properties, reflection loss, and absorption bandwidth. This chapter also investigates the impact of adding MWCNTs on absorption performance compared to pure DBL. The results showed that the inclusion of MWCNTs significantly enhanced the absorption capabilities, demonstrating the potential of DBL-MWCNT composites as a lightweight, low-cost, and sustainable solution for practical applications, including electromagnetic interference (EMI) shielding and stealth technology.

4.2. Microwave Absorber Sample Fabrication Method for DBL and DBL-MWCNT Composites

The primary raw materials used for fabricating the microwave absorber included DBL, MWCNT, and polyester resin, as shown in Figure 4.1(a-c). The MWCNTs utilized in this fabrication have a high purity of 97%, a surface area ranging between $90\text{--}220\text{ m}^2/\text{g}$ have a typical length of approximately $10\text{ }\mu\text{m}$, with a diameter falling within the range of $5\text{--}20\text{ nm}$.



Figure 4.1. Primary raw materials used for fabrication MA (a) Banana leaves waste (b) MWCNTs (c) polyester resin (d) powder form of banana leaves and (e) MWCNTs powder

4.2.1 Pre-processing of Raw Materials

The fabrication process begins with the collection of green banana leaves, an agricultural byproduct often discarded as waste. These leaves are initially washed thoroughly with water to eliminate dust and any other surface contaminants. Following this cleaning, the leaves are subjected to natural drying under sunlight for a duration of approximately 3-4 weeks to ensure complete moisture removal. Once dried, the leaves are processed into a fine powder using a household-grade mechanical grinder. The resultant powder is then passed through a sieve to obtain a more uniform particle size distribution. Despite the sieving process, the particle sizes

remain non-uniform, typically ranging from $140\ \mu\text{m}$ to $520\ \mu\text{m}$, as illustrated in Figure 4.1(d). Simultaneously, the powdered form of MWCNTs is shown in Figure 4.1(e).

4.2.2 Composite Formation of DBL-MWCNTs

The fabrication process of the DBL-MWCNTs composite is visually summarized in Figure 4.2.

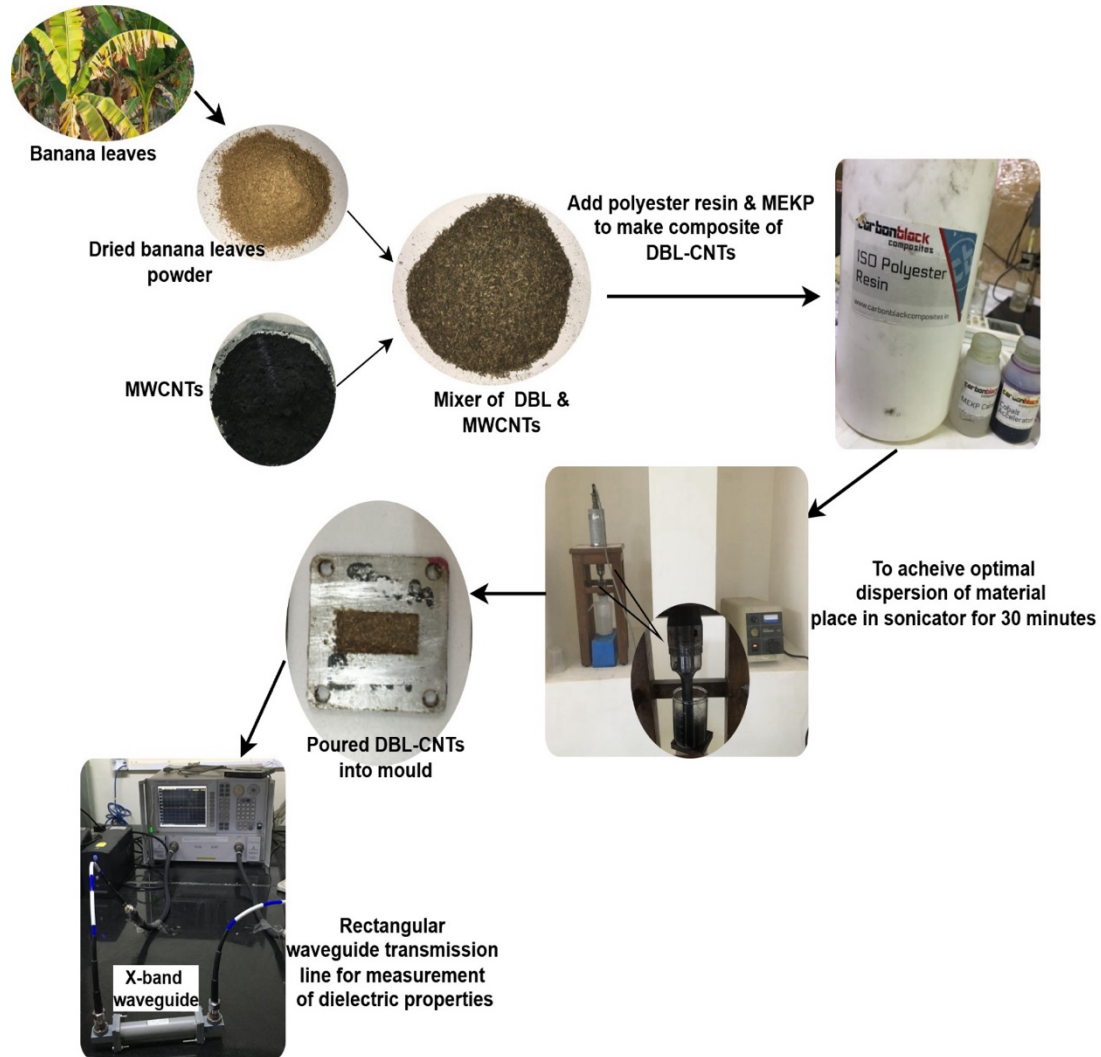


Figure 4.2 Preparation Procedure of Dried Banana Leaves-MWCNT Rectangular Composites

Initially, the dried banana leaves (DBL) powder is mixed with different weight fractions of MWCNTs, which act as the functional filler material. In this chapter, composites were prepared using three different MWCNT loadings: 1 wt.%, 3 wt.%, and 5 wt.%. To achieve uniform dispersion and strong interaction between the filler and matrix, the MWCNTs and DBL powders are thoroughly mixed. Subsequently, a PR is introduced as the primary binding agent, along with MEKP as the hardening agent. Cobalt is also added to accelerate the curing reaction. The mixture is then subjected to ultrasonic agitation using a sonicator for 30-35 minutes to achieve optimal dispersion at the microscopic level, preventing agglomeration of the nanotubes

and enhancing the overall homogeneity of the composite. Following this, the well-dispersed slurry is poured into pre-fabricated rectangular moulds with dimensions of $22.86\text{mm} \times 10.16\text{mm} \times 2\text{mm}$. The filled moulds are then allowed to cure at ambient temperature for a period of 24 hours. The resin-to-hardener weight ratio is carefully maintained at 5:1 throughout the fabrication process to ensure consistent mechanical and structural integrity. After completing the curing stage, all fabricated composite samples were carefully demoulded. A total of eight rectangular-shaped samples were successfully prepared using above mentioned fabrication steps. These samples were developed using varying combinations of DBL powder, polyester resin, and MWCNT fillers, with the intent to investigate how filler concentration and thickness affect microwave absorption behaviour. Each sample was designated a specific code, as detailed in Table 4.2, to systematically track the variations in material composition and thickness. Among the eight samples, two were made using only dried banana leaves without adding any MWCNT content. The remaining six samples incorporated MWCNTs as fillers in three different weight percentages: 1 wt%, 3 wt%, and 5 wt%, with each concentration tested at two thickness levels: 2 mm and 4 mm. To evaluate the electromagnetic properties of these. Each sample was tested individually using a rectangular waveguide transmission line setup. This experimental setup is specifically designed to evaluate the dielectric properties and microwave absorption characteristics of the composite within the X-band frequency range. The geometrical configuration for all samples was kept constant, with mould dimensions fixed at $22.86\text{mm} \times 10.16\text{mm}$. The thicknesses were either 2 mm or 4 mm, varying on specific sample design. The weight of DBL powder, amount of polyester resin and hardener, and MWCNT filler content used for each sample are comprehensively summarized in Table 4.2.

Table 4.2. Fabrication Parameters and Dimensional Details of Composite Samples

Samples	Amount of Dried banana leaves (gm)	Resin and hardener (gm)	MWCNTs fillers		Mould dimensions (mm)	Sample thickness (mm)	Sample code
			(gm)	wt. %			
Pure dried banana leaves	2	3	0	0	22.86×10.16	2	B1 ₂
Pure dried banana leaves	3	4	0	0	22.86×10.16	4	B1 ₄
Dried banana leaves + 1wt%MWCNTs	2	3	0.05	1	22.86×10.16	2	BCN2 ₂
Dried banana leaves + 1wt%MWCNTs	3	4	0.07	1	22.86×10.16	4	BCN2 ₄

Dried banana leaves + 3wt%MWCNTs	2	3	0.15	3	22.86×10.16	2	BCN3 ₂
Dried banana leaves + 3wt%MWCNTs	3	4	0.21	3	22.86×10.16	4	BCN3 ₄
Dried banana leaves + 5wt%MWCNTs	2	3	0.25	5	22.86×10.16	2	BCN4 ₂
Dried banana leaves + 5wt%MWCNTs	3	4	0.35	5	22.86×10.16	4	BCN4 ₄

4.3 Techniques for Sample Characterization and Electromagnetic Measurement

4.3.1 Experimental setup

In this chapter, the rectangular waveguide transmission line technique was adopted to measure the dielectric behaviour of samples across the X-band frequency range. Prior to beginning the measurements, the experimental setup was thoroughly calibrated using the SOLT calibration standard. This calibration procedure is essential for minimizing systematic errors and ensuring accurate and consistent results. Each fabricated sample was precisely cut and inserted into a specially designed sample holder, the dimensions of which were fixed at $a = 22.86\text{mm}$, $b = 10.16\text{mm}$, and thicknesses of either 2mm or 4mm , as illustrated in Figure 4.3(a). The dielectric properties of all eight samples namely B1₂, B1₄, BCN2₂, BCN2₄, BCN3₂, BCN3₄, BCN4₂, and BCN4₄ were evaluated individually.

Measurements were taken in the X-band using a rectangular waveguide (11164A) linked to a VNA (N5230C) through coaxial cables, as shown in Figure 4.3(b) and Figure 4.3(c). The physical dimensions of the test samples, particularly length 22.86mm and width $=10.16\text{mm}$, are shown in Figure 4.3 (d).

The real part ϵ' and imaginary part ϵ'' of the complex dielectric was obtained over the 8.2-12.4 GHz range. Furthermore, the dielectric loss tangent and electrical conductivity of each sample were calculated using Equation (3.2) and Equation (3.11), respectively.

4.3.2 Measurement of Sample Thickness

Sample thickness significantly affects microwave absorption efficiency, as small changes can alter dielectric behaviour and wave interaction. [99]. Therefore, accurate measurement of thickness is important for proper evaluation of the absorber's performance. To ensure precision, the thickness of each fabricated sample was measured using a digital caliper, as illustrated in the Figure. 4.4.

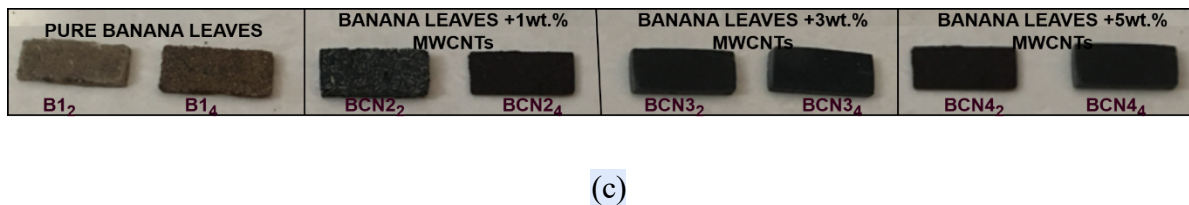
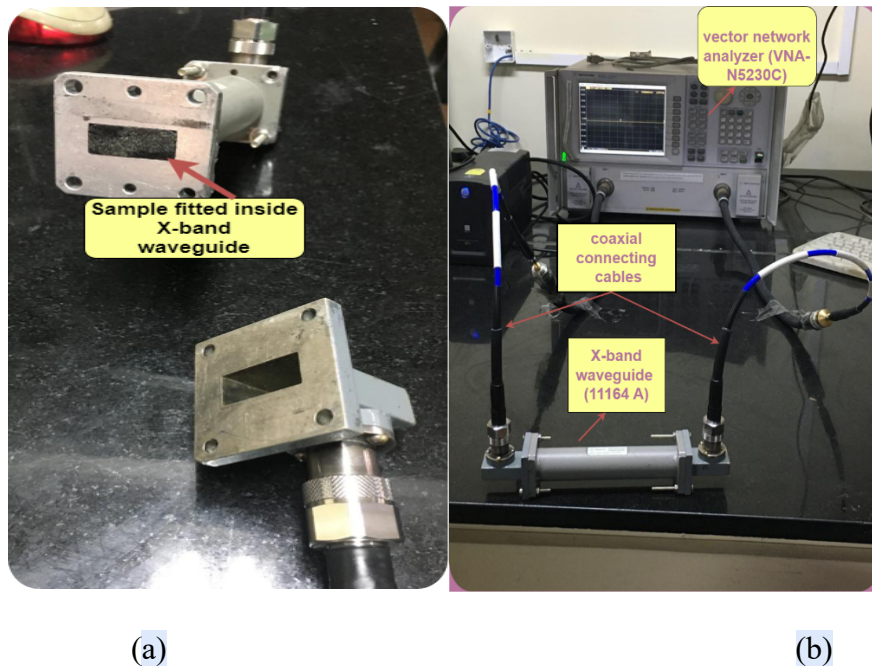


Figure 4.3 Experimental Setup and Prepared Samples (a) Measurement setup using the rectangular waveguide transmission line technique, (b) Composite sample accurately positioned within the X-band waveguide slot, (c) Fabricated DBL-MWCNT composite samples ready for testing, (d) Individual sample with specified dimensions: length = 22.860 mm and width = 10.160 mm.



4.3.3 Particle size measurements

The grain size of powdered material plays an important role in influencing its microwave absorption performance [40]. The particle size distribution of DBL powder was analyzed using an optical microscope equipped with a $50\times$ magnification lens. As shown in Figure. 4.5(a) and Figure. 4.5(b), the microscope setup was used to observe the morphology and measure the size of individual particles. The microscopic image reveals that the particles are irregular in shape and vary significantly in size, primarily due to the mechanical grinding and sieving process used during sample preparation. The particle sizes of the DBL powder were observed to fall within a non-uniform range, approximately between $95\ \mu\text{m}$ and $580\ \mu\text{m}$. Smaller particles provide a higher surface-to-volume ratio, increased porosity, and more active surface sites, all of which contribute to improved dielectric properties and enhanced attenuation of electromagnetic waves. The relationship between particle size and surface area is mathematically represented by the following expression, equation (4.1):

$$A_s \propto \frac{1}{r} \quad (4.1)$$

where A_s is the specific surface area and r represents the particle radius.

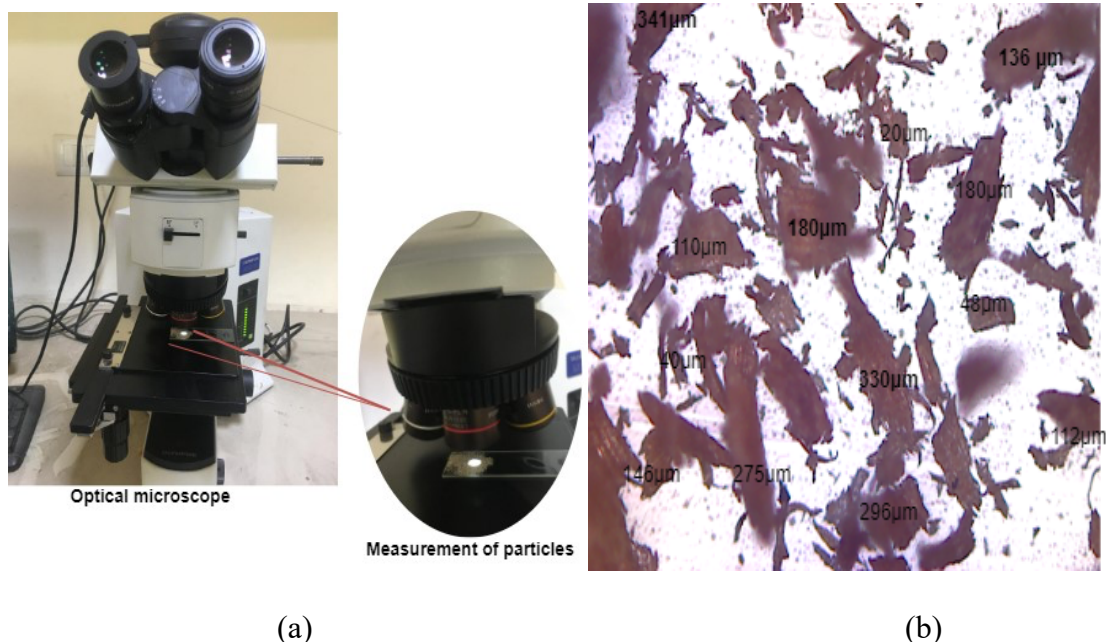
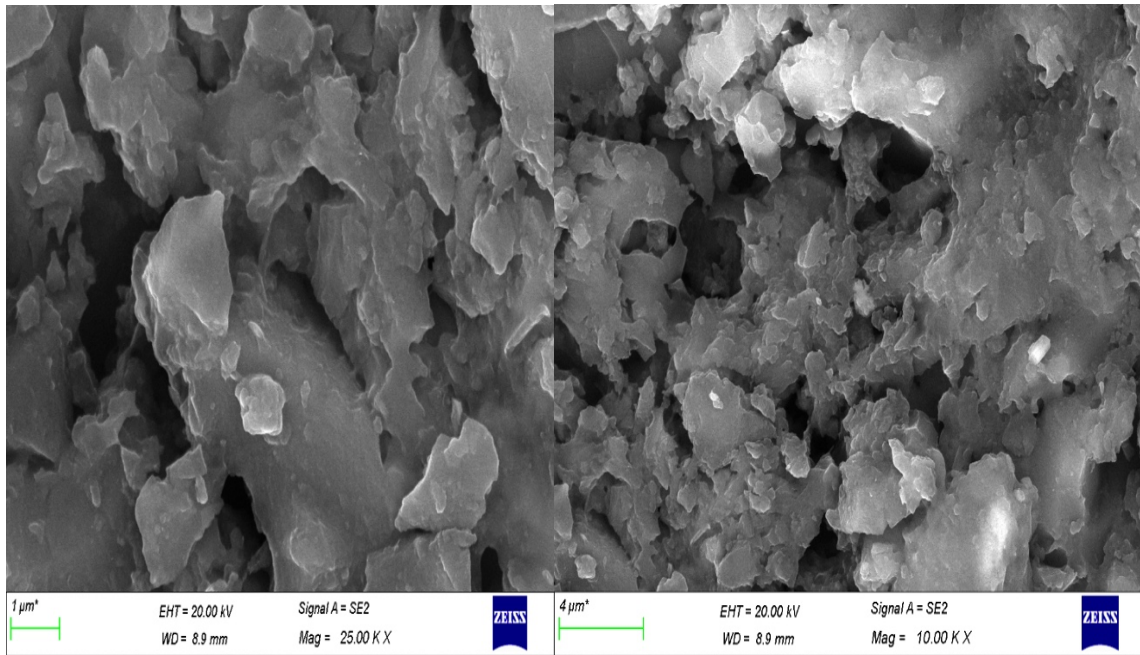


Figure 4.5 Particle measurement setup (a) Experimental setup showing the optical microscope used for analyzing DBL powder particle size at $50\times$ zoom.(b) Microscopic image illustrating the shape and size variation among particles of the dried banana leaf powder.

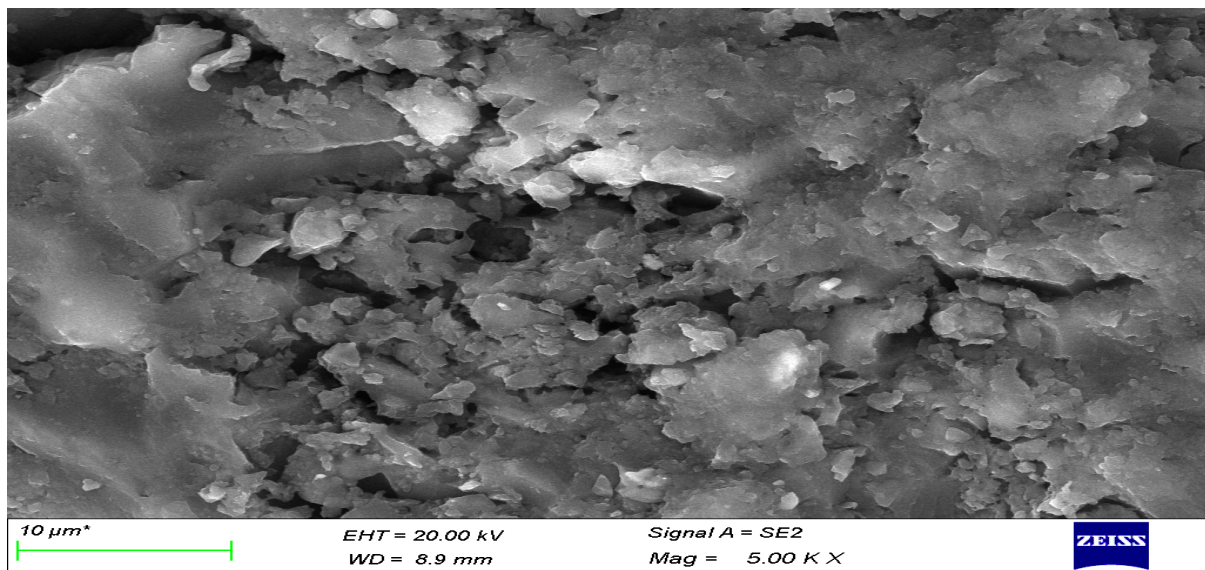
4.4 Microstructural and Elemental Analysis via SEM-EDX

4.4.1 Scanning Electron Microscopy (SEM)



(a)

(b)



(c)

Figure 4.6. SEM images of DBL-MWCNTs composite material taken at different magnifications. (a) $1\ \mu\text{m}$, (b) $4\ \mu\text{m}$, and (c) $10\ \mu\text{m}$, illustrating surface morphology, compact structure, and porosity.

Figure 4.6 (a-c) presents scanning electron microscope (SEM) images of the DBL-MWCNTs composite, captured at various magnifications to examine its surface morphology. At higher magnifications, the surface appears compact and dense, while lower magnifications reveal a

rough and uneven sheet-like structure with fractured edges. This heterogeneous structure indicates a strong interfacial bonding between the MWCNTs and the DBL matrix. Interconnected pores and voids are clearly observed across the composite, contributing significantly to improved microwave absorption. These porous features are particularly effective in scattering and dissipating electromagnetic energy. Thus, the microstructural characteristics revealed by SEM images confirm that composite possesses a mechanically stable structure with high potential for absorbing microwave radiation.

4.4.2 SEM and Energy-Dispersive X-ray Spectroscopy (EDS) Analysis

Figure 4.7 shows a SEM image of the DBL-MWCNTs composite material taken at a magnification of 2500 $\times$, with a scale bar representing 20 μm . The image reveals the detailed topography of the surface, where both fibrous and granular features are distinguishable. These visible components correspond to the MWCNTs integrated with DBL powder.

To investigate the elemental composition of the composite, Energy-Dispersive X-ray Spectroscopy (EDS) was performed at four distinct spots, marked as B4.1, B4.2, B4.3, and B4.4 in the SEM image. The corresponding elemental data is summarized in Table 4.3. The EDS results highlight the variation in carbon concentration at different points on the sample surface.

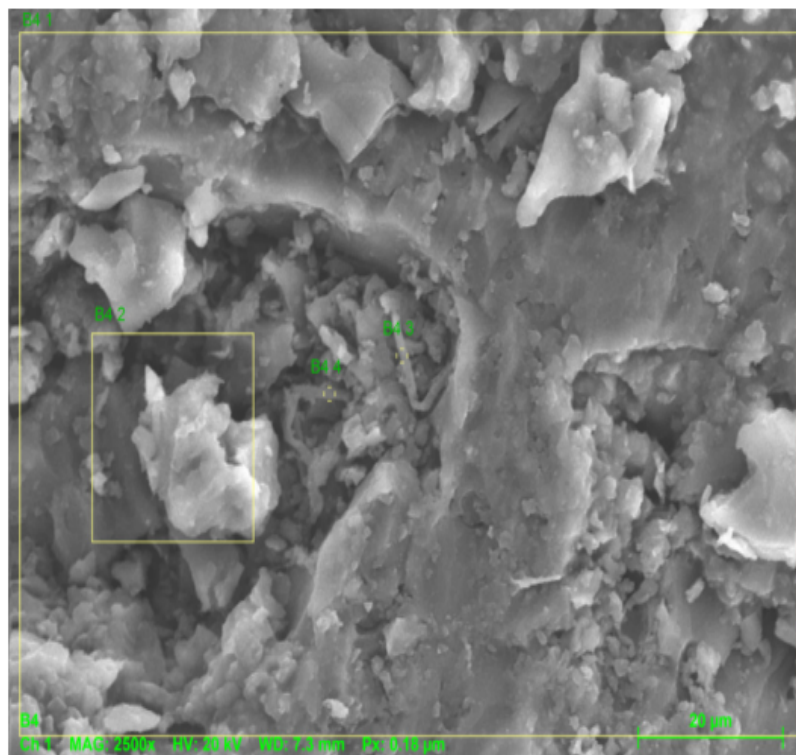


Figure 4.7 SEM image of DBL-MWCNTs composite at 2500 $\times$ magnification with marked spots (B4.1 to B4.4) where EDS elemental analysis was conducted.

Table 4.3 Elemental Composition of DBL-MWCNTs Composite (EDS Analysis)

ELEMENTS	Carbon (C)	Oxygen (O)	Chlorine (Cl)
B4. 1	77.53	20.07	1.37
B4. 2	78.199	19.33	1.34
B4. 3	83.46	14.01	1.12
B4. 4	87.17	10.54	1.22

At point *B4.1*, the composition reveals 77.53% carbon and 20.07% oxygen. Similarly, *B4.2* records 78.20% carbon and 19.33% oxygen. Points *B4.3* and *B4.4*, located primarily on the MWCNT regions, show elevated carbon levels of 83.46% and 87.17%, respectively, with a corresponding reduction in oxygen content. These observations suggest that the integration of 5 wt.% MWCNTs into the DBL matrix significantly increases the carbon concentration of the resulting composite compared to the base DBL material, which originally contained only 42.34% carbon (as listed in Table 4.1).

The increase in carbon content is highly beneficial for microwave absorption applications. Carbon-rich materials possess superior electrical conductivity and elevated dielectric loss, both of which contribute to the efficient transformation of incident electromagnetic energy into thermal energy. A higher carbon content also increases the material's complex permittivity [10]. Improving its ability to store and dissipate electromagnetic energy. Thus, the EDS findings confirm that the addition of MWCNTs substantially improves EM response of the DBL-based composite.

4.5 Dielectric Behaviour of DBL-MWCNTs Based Microwave Absorbers

A crucial factor in assessing the effectiveness of microwave absorber materials is their dielectric behaviour, as it represents the material's capacity to store incoming electromagnetic energy and dissipate it as heat. In this chapter, the dielectric characteristics of several fabricated samples B1₂, B1₄, BCN2₂, BCN2₄, BCN3₂, BCN3₄, BCN4₂ and BCN4₄ were examined using a VNA connected to a WR-90 waveguide, which operates within the X-band frequency range (8.2–12.4 GHz). Among these, B1₂, B1₄ are samples composed solely of dried banana leaves (DBL), while the rest BCN2₂, BCN2₄, BCN3₂, BCN3₄, BCN4₂ and BCN4₄ are DBL-based composites incorporating MWCNTs in varying loadings of 1 wt.%, 3 wt.%, and 5 wt.% at two different thicknesses: 2 mm and 4 mm, respectively. Experimental findings indicate that these DBL-MWCNTs composites behave as non-magnetic dielectric materials in the X-band

frequency range, as evidenced by their magnetic permeability (μ) being equal to 1. Additionally, the materials exhibit minimal electromagnetic energy loss, as reflected by the low loss factor values.

To ensure accuracy and reliability, the average dielectric values for each sample were computed across the entire X-band using Equation (3.17)

The average dielectric constants calculated for all fabricated samples are presented in Table 4.4, providing a comparative overview of how MWCNT loading and sample thickness influence the composite's dielectric response.

Table 4.4 Average Dielectric Characteristics Across X-Band for Fabricated Materials

Parameters	Samples with 2mm and 4mm Thickness							
	B1 ₂	B1 ₄	BCN2 ₂	BCN2 ₄	BCN3 ₂	BCN3 ₄	BCN4 ₂	BCN4 ₄
ϵ'	2.71	3.09	4.17	5.4	4.7	6.4	6.5	8.5
ϵ''	0.20	0.25	0.54	0.63	0.65	0.96	0.99	1.5
$\tan \delta$	0.06	0.08	0.123	0.13	0.14	0.15	0.145	0.19
σ (S/m)	0.11	0.13	0.27	0.31	0.32	0.49	0.48	0.78

The measured dielectric constants for the fabricated samples B1₂, B1₄, BCN2₂, BCN2₄, BCN3₂, BCN3₄, BCN4₂ and BCN4₄ were found to be 2.71, 3.09, 4.17, 5.4, 4.7, 6.4, 6.5, and 8.5, respectively. These values indicate a consistent increase in dielectric constant with the increment of MWCNT content and sample thickness, confirming that both parameters play a significant role in improving electromagnetic energy storage capability.

Figure 4.8(a) illustrates that the dielectric constant decreases as frequency increases [44]. This behaviour is attributed to the limited response time of dipoles at higher frequencies they are unable to align rapidly with the alternating electric field, resulting in delayed polarization, which reduces the dielectric constant. Figure 4.8(b) shows the dielectric loss factor, representing the ability of the material to dissipate EM energy as heat. This energy loss, which is essential for microwave absorption, is mainly governed by polarization mechanisms in dielectric materials, such as electronic, atomic, interfacial, and dipolar polarization, as shown in Figure 4.9.

When dipoles lag behind the applied electric field due to slow alignment, relaxation losses occur, leading to internal energy dissipation. The dielectric loss tangent, shown in Figure

4.8(c), quantifies the energy dissipated during polarization relaxation under the impact of an external field. Peaks in loss tangent spectrum across the X-band frequency range indicate effective absorption characteristics of the composites, validating their usefulness in microwave attenuation applications. Electrical conductivity of the samples is presented in Figure 4.8(d). A high conductivity, paired with low electrical resistance, contributes significantly to the overall dielectric loss, particularly the conduction loss component of the complex permittivity. Thus, the energy loss in such materials stems not only from polarization but also from the movement of charge carriers within conductive network.

Notably, the BCN4₂ sample, composed of 5 wt.% MWCNTs at 2 mm thickness, recorded a dielectric loss of 0.9, loss tangent of 0.14, and conductivity of 0.48 S/m. In comparison, BCN4₄ with the same MWCNT content but a thickness of 4 mm, exhibited higher values of dielectric loss of 1.5, loss tangent of 0.19, and conductivity of 0.78 S/m (as seen in Table 4.3). On the other end, the samples B1₂, B1₄, made entirely from DBL without MWCNTs, demonstrated the lowest dielectric loss, tangent loss, and conductivity at both 2 mm and 4 mm thicknesses. According to Figures 4.10(a-d), the inclusion of 5 wt.% MWCNTs and increased thickness markedly improve the dielectric response of the composite. The enhancements are due to the increased surface area, porosity, and number of active sites in the composite. These microstructural features, observed in SEM and EDX images, confirm the formation of a porous matrix with high interfacial interaction, which contributes to improved polarization mechanisms. The formation of more dipoles within the composite improves its polarization response under electromagnetic radiation shown in Figure 4.9. Furthermore, the amorphous carbon structure in MWCNTs, being non-crystalline, supports dielectric relaxation losses, contributing further to the energy dissipation process. The integration of MWCNTs forms conductive pathways within the composite, which elevate conductivity and reinforce the absorption of electromagnetic waves.

This relationship between dielectric loss and conductivity is represented in Equation (3.18)

ϵ'' is the dielectric loss and σ is the conductivity. This equation clearly shows that as conductive filler content increases, conduction loss also rises. In the absence of fillers, as seen in B1₂, B1₄, the conductivity is negligible, and thus conduction-related losses are minimal. However, for a sample like BCN4₄, with a high MWCNT concentration and greater thickness, conduction loss becomes the dominant contributor to total dielectric loss.

Experimental results clearly demonstrate that BCN4₂ and BCN4₄ both containing 5 wt.% MWCNTs show significantly enhanced dielectric behaviour, validating the positive impact of both filler loading and structural configuration on microwave absorption efficiency

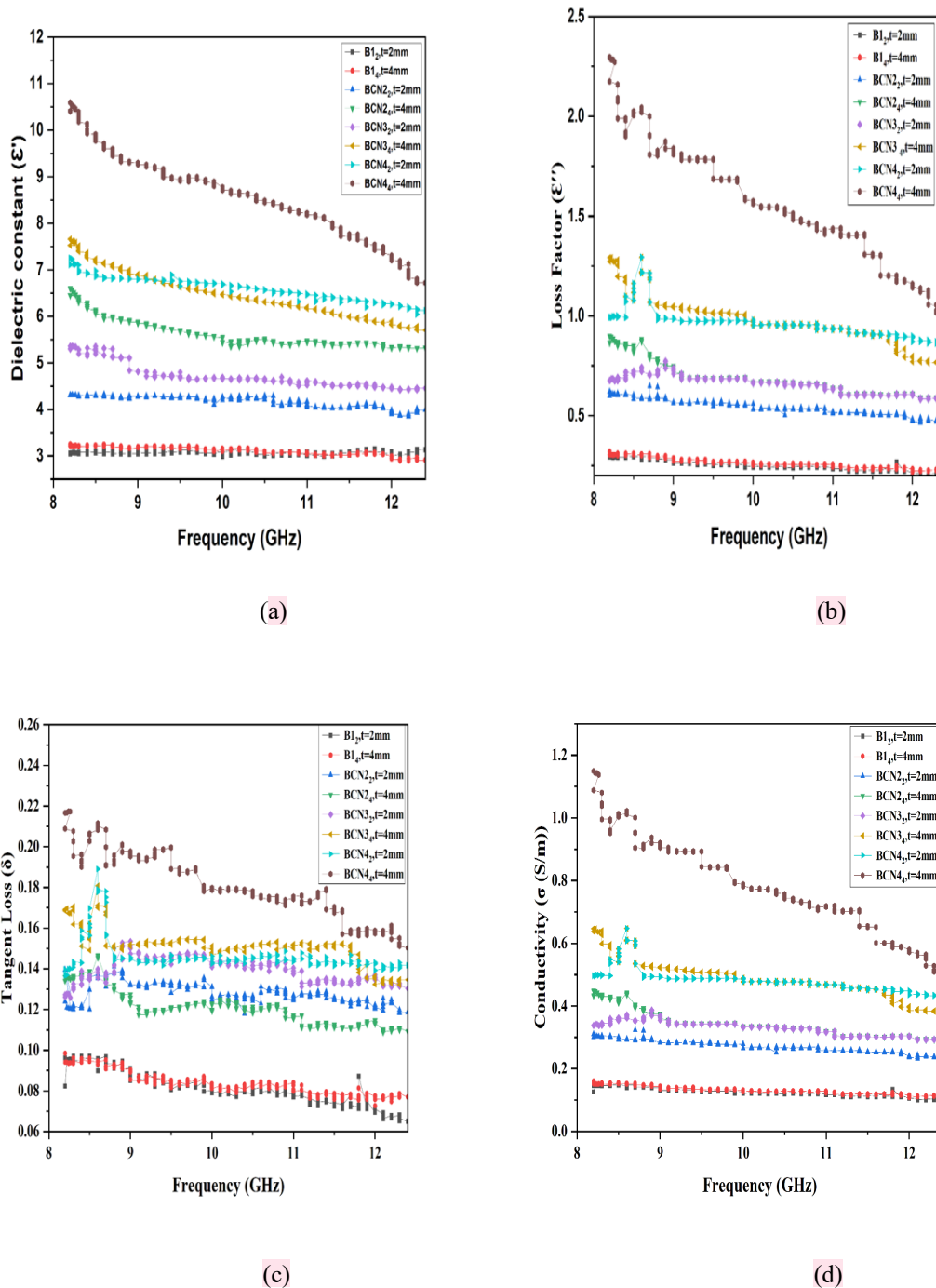


Figure 4.8 Dielectric properties of DBL and DBL-MWCNTs composites with 2 mm and 4 mm thicknesses at different MWCNT loadings: (a) Dielectric constant, (b) Dielectric loss, (c) Loss tangent, and (d) Electrical conductivity.

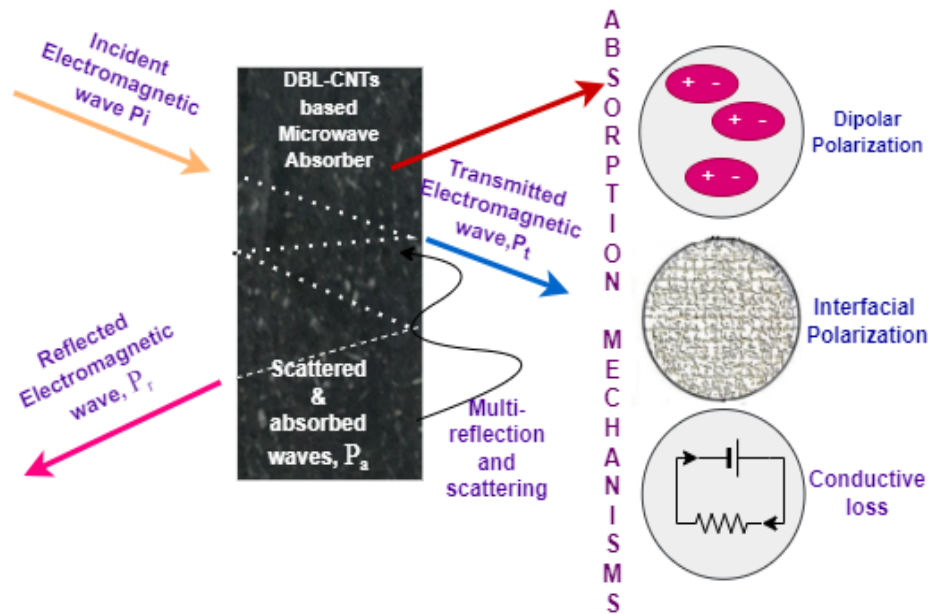


Figure 4.9. Microwave Absorption Mechanisms in DBL-MWCNTs Based Absorber

4.6 Reflection Loss Behaviour and Absorption Efficiency of Composites

The microwave absorption behaviour of a material is significantly influenced by dielectric properties, conductivity, and thickness. As expressed in Equation (3.18), both conductivity and dielectric loss factor contribute to heat generation, which plays a key role in microwave attenuation. Enhancing the dielectric performance of a material, therefore, directly improves its absorption efficiency [168]. In this chapter, MWCNTs were incorporated into dried banana leaves (DBL) to develop heterogeneous composites with improved microwave absorption capabilities. The RL of fabricated samples was evaluated using Equation (4.2), which incorporates the material's complex permittivity (ϵ_r), permeability (μ_r) sample thickness (t), the operating frequency (f), the speed of light in free space (c), and both input impedance (Z_{in}) and free space impedance (Z_0).

$$RL = 20 \log \left| \frac{Z_{in} - Z_0}{Z_{in} + Z_0} \right| \quad (4.2)$$

$$Z_{in} = Z_0 \sqrt{\mu_r / \epsilon_r} \tanh \left[j \frac{2\pi f d}{c} \sqrt{(\mu_r \epsilon_r)} \right] \quad (4.3)$$

Since the DBL-MWCNT composites are derived from biowaste, their relative permeability (μ_r) is considered to be 1, indicating a non-magnetic behaviour of the materials used. Figure 4.10 presents the reflection loss behaviour of all fabricated samples within the X-band at two different thicknesses: 2 mm and 4 mm. At 4 mm, pure DBL and composites containing 1 wt.%,

3 wt.%, and 5 wt.% of MWCNTs were tested. A distinct improvement in RL was observed with increasing MWCNT content. For instance, sample BCN4₄ (5 wt.% MWCNTs) recorded a peak RL of -50.8 dB, followed by BCN3₄ and BCN2₄, with RL values of -34.8 dB and -28 dB, respectively. In contrast, the pure DBL sample (B1₄) displayed the lowest RL value of -12.94 dB, as summarized in Table 4.5.

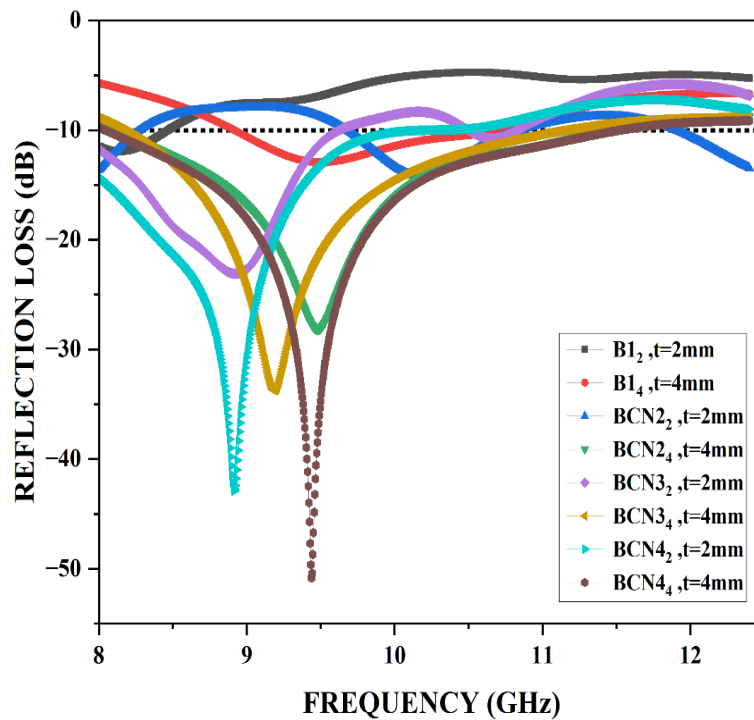


Figure 4.10 Measured RL of Composite Absorbers Across X-Band Frequencies

Table 4.5. Microwave absorption parameters of pure DBL & DBL-MWCNTs at a thickness of 4mm.

Material	Composite	Material Dimensions (mm)	Thickness (mm)	Reflection loss (dB)	Frequency (GHz)	Bandwidth below -10dB (GHz)
Pure dried banana leaves	-	22.86×10.16	4	-12.94	9.5	0.7(9.2-10.1)
Pure dried banana leaves	1wt%MWCNTs	22.86×10.16	4	-28	9.5	3 (8.2-11.2)
Pure dried banana leaves	3wt%MWCNTs	22.86×10.16	4	-34.8	9.4	3.4 (8.1-11.5)
Pure dried banana leaves	5wt%MWCNTs	22.86×10.16	4	-50.8	9.4	3.7(8.0-11.7)

Table 4.6 Microwave absorption parameters of pure DBL & DB-MWCNTs at a thickness of 2mm.

Material	Composite	Material Dimensions (mm)	Thickness (mm)	Reflection loss (dB)	Frequency (GHz)	Bandwidth below -10dB (GHz)
Pure dried banana leaves	-	22.86×10.16	2	-11.53	8.3	0.5 (8.21-8.34)
Pure dried banana leaves	1wt%MWCNTs	22.86×10.16	2	-14.2	10.1	1.09 (9.61-10.7)
Pure dried banana leaves	3wt%MWCNTs	22.86×10.16	2	-23.11	8.9	1.43 (8.2-9.63)
Pure dried banana leaves	5wt%MWCNTs	22.86×10.16	2	-42.9	8.9	2.53(8.2-10.73)

The bandwidth below -10 dB also increased with the filler content, reaching 3.7 GHz for BCN₄, compared to just 0.7 GHz for B₁. This highlights the significance of MWCNTs in improving the frequency range over which substantial microwave absorption is achieved. However, due to the larger thickness, some samples were unsuitable for compact aerospace applications. To address this, thinner samples (2 mm) were fabricated to assess their suitability for military and stealth-related uses. Table 4.6, reflection loss values for thinner samples also improved with MWCNT content: B₁ (pure DBL) showed -11.53 dB, while BCN₂, BCN₃, and BCN₄ reached -14.2 dB, -23.11 dB, and -42.9 dB, respectively. The absorption bandwidth at 2 mm for BCN₄ spanned 2.53 GHz, which is considered highly efficient for thin absorbers.

4.7 Absorbed Power Estimation

When an electromagnetic wave encounters a sample backed with a metallic plate, a portion of the wave is reflected, and the rest is absorbed no transmission occurs. The percentage of absorbed power can be estimated from the reflection loss using Equation (4.17):

$$\text{Absorption \%} = 100 - \text{Reflected power} = \left[100 - 100 * \left(10^{(-RL/10)} \right) \right] \quad (4.4)$$

Figure 4.11 shows the power absorption trends of all samples. Pure DBL (B₁ and B₁) absorbed about 91.7% of incident energy at 9.76 GHz. When 1 wt.%, 3 wt.%, and 5 wt.% MWCNTs were introduced into DBL composites (at 2 mm thickness), the absorption improved to 96.1% at 10.2 GHz, 99.46% at 8.9 GHz, and 99.8% at 9.02 GHz, respectively. At a thickness of 4 mm, absorption capacity further improved. DBL composites with 1 wt.%, 3 wt.%, and 5 wt.% MWCNTs showed absorptions of 99.7%, 99.8%, and 99.9%, respectively, at 9.4 GHz, 9.5 GHz, and 9.43 GHz.

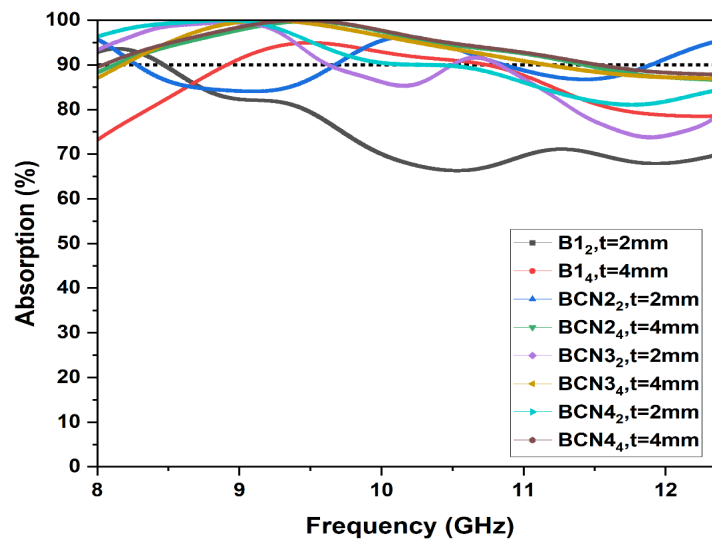


Figure 4.11 Power absorption characteristics of fabricated samples for X-band.

Among all the tested samples, the composite BCN4₄ (5 wt.% MWCNTs, 4 mm thick) displayed the broadest and most effective absorption, covering a frequency range from 8.02 GHz to 11.3 GHz, with maximum power absorption exceeding 99%.

4.8 Comparative Evaluation of Microwave Absorption in Biowaste-Derived Composite Materials

Table 4.7 presents a comparative analysis of dielectric characteristics and EM wave absorption performance of various biowaste-based composite materials, including the DBL-MWCNT composites developed in this chapter. Among the samples evaluated, the composite consisting of DBL with 5 wt.% MWCNTs at 2 mm thickness demonstrated a dielectric constant of 6.5 and a dielectric loss tangent of 0.14. This sample achieved a peak RL of -42.9 dB at 8.9 GHz and an effective absorption bandwidth (for $RL \leq -10$ dB) of 2.29 GHz within the X-band range. Furthermore, increasing the sample thickness to 4 mm while maintaining the same filler loading (5 wt.% MWCNTs) led to a significant enhancement in microwave absorption. The RL reached a maximum of -50.8 dB, accompanied by an expanded absorption bandwidth of 3.7 GHz. These improvements clearly indicate that both the addition of conductive fillers like MWCNTs and an increase in absorber thickness contribute positively to the dielectric and electromagnetic attenuation behaviour of the bio-composite. When compared with other natural and waste-derived composites such as rice husk ash, coconut coir, and sugarcane bagasse-based absorbers, the DBL-MWCNT composites exhibit superior performance, particularly in terms of lower reflection loss and broader absorption bandwidth. This highlights the potential of dried banana

leaves, an agricultural residue, in combination with carbon nanostructures, to serve as a cost-effective, sustainable solution for X-band microwave absorption applications.

Table 4.7. Comparative Study on the Dielectric and Microwave Attenuation Capabilities of Agricultural Waste Composites

Material	Composite	Dielectric constant	Thickness (mm)	Frequency (GHz)	Reflection loss (dB)	Bandwidth (GHz)	reference
Banana leaves	-	2.78	15.98	2-18	-25.6	1.133	[10]
Banana leaves	Charcoal 0.028wt%	5.23	1.50	1-20	-25.29	0.8	[126]
bael leaves	-	-	9	8-12.5	-27.12	1.60	[55]
Corn husk	Charcoal 4.44wt. %	3.9	1.08	1-20	-50.2	1.6	[107]
Rice husk ash	polyester	4.80	20	12.4-18	-28.4	0.81	[70]
Rice husk ash	CNTs 2wt%	5.586	10	2-18	-20.4	3.2	[124]
Double layer Rice husk	CNTs 5 wt. %	7.08	10	2-18	-37.2	5.1	[131]
Rice husk	CNTs 5 wt. %	3.96	5	12.4-18	-32	3.6	[132]
Rice husk	CNTs 3 wt. %	6.4	8	8.2-12.4	-33.7	1.8	[124]
Coconut coir dust	Epoxy 80 wt. %	3.32	3	8.2-12.4	-23.5	2.03	[106]
Raphael powder	-	2.11	7	8.2-12.4	-42.7	0.43	[108]
Sugarcane bagasse	Rubber tire dust 50 wt. %	3.38	5	12.4-18	-13.2	-	[118]
Dried banana leaves	MWCNTs 5 wt. %	6.5	2	8.2-12.4	-42.9	2.53	Work done
Dried banana leaves	MWCNTs 5 wt. %	8.5	4	8.2-12.4	-50.8	3.7	Work done

4.9 Summary and Contribution of the Chapter

This chapter presented a detailed investigation into the development of a bio-composite microwave absorber using DBL and MWCNTs. Highlighting was placed on material processing, structural and elemental characterization, and evaluation of EM wave behaviour across the X-band frequency range. The fabrication process began with sun-drying and mechanical grinding of banana leaves, followed by sieving to obtain a fine powder. This powder was combined with MWCNTs in varying weight percentages (1%, 3%, and 5%) and uniformly dispersed using polyester resin as the binding matrix. The composites were moulded into rectangular shapes with two targeted thicknesses, 2 mm and 4 mm, allowing systematic assessment of geometric influence on absorption behaviour. Microscopy techniques confirmed the presence of a diverse particle size distribution and a porous microstructure. Optical imaging

revealed irregular granularity, while SEM micrographs showed embedded nanotubes well-integrated into the DBL matrix. Elemental analysis through EDS indicated an increasing carbon concentration correlating with higher MWCNT loading, confirming the effectiveness of the filler in enhancing conductive pathways within the bio-composite. Electromagnetic characterization performed using a VNA and *WR-90* waveguide showed that increasing the MWCNT content significantly improved dielectric performance. Samples with 5 wt.% MWCNTs exhibited high dielectric loss and enhanced conductivity, improved charge mobility, and polarization behaviour. The improvement in these properties led to stronger energy attenuation.

The RL analysis further covered this outcome. The sample with 5 wt.% MWCNTs and 4 mm thickness (BCN4₄) achieved a peak *RL* of -50.8 dB with a wide effective bandwidth of 3.7 GHz, making it one of the most efficient absorbers among the tested samples. Even the thinner variant (BCN4₂, 2 mm) demonstrated considerable absorption, with *RL* reaching -42.9 dB, highlighting the composite's suitability for compact, lightweight absorber applications in military vehicles, submarines, and fighter jets. When compared with other reported biowaste-derived microwave absorbers, such as rice husk ash, corn husk charcoal, sugarcane bagasse, and coconut coir dust, the DBL-MWCNT composites show clear advantages in both reflection loss and bandwidth. For instance, while materials like rice husk with CNTs or corn husk charcoal exhibit good absorption, their performance often requires higher filler content or greater thickness. In contrast, the DBL-MWCNT composites achieved superior results even at relatively low filler loading and reduced thickness, highlighting the effectiveness of DBL intrinsic carbonaceous structure in combination with conductive nanomaterials.

Overall, this chapter shows that dried banana leaves combined with a small amount of MWCNTs form an efficient, eco-friendly microwave absorber. Improved dielectric properties and absorption performance arise from enhanced interfacial polarization, conductive networks, and optimized microstructure, highlighting the potential of DBL-MWCNT composites for lightweight EMI shielding and stealth applications

PUBLISHED WORK RELATED TO THIS CHAPTER:

1. A. Tripathi and K. S. Sandha, "Broad microwave absorption bandwidth analysis of biocomposite microwave absorber material for X-band applications," *Biomass Conversion and Biorefinery*, vol. 15, no. 9, pp. 13977–13995, 2025. (SCI indexed- Impact Factor – 4.1)

CHAPTER-5

MICROWAVE ABSORPTION PERFORMANCE OF SUGARCANE BAGASSE/MWCNT COMPOSITE MATERIALS

This chapter discusses and analyzes the microwave absorption properties of a composite made from sugarcane bagasse with Multiwalled carbon nanotubes (MWCNTs). It begins with the fabrication of the sugarcane bagasse-MWCNT composite samples, followed by an evaluation of several key parameters to assess their suitability as microwave absorbers. These parameters include dielectric properties, dielectric loss tangent, electrical conductivity, reflection loss, and absorption percentage. The aim of this analysis is to determine the material's effectiveness in absorbing electromagnetic waves. All characterizations were conducted within the X-band frequency range, enabling a detailed examination of the composite's absorption behaviour under standard microwave operating conditions.

5.1 INTRODUCTION

Agricultural waste management presents a significant challenge in sustainable development, particularly in agricultural economies like India. Among various plant-based residues, sugarcane bagasse (SG) is notable as one of the most abundantly produced byproducts in the agro-industrial sector's is the fibrous biomass residue left after extracting juice from sugarcane, mainly for sugar production. For every 1000 kilograms of raw sugarcane processed, about 280 kilograms of sugarcane bagasse (SG) is produced. Global estimates indicate that over 54 million dry tons of SG were generated worldwide in 2005. India ranks second in sugarcane production, generating substantial agricultural waste, particularly in major sugar-producing states such as Uttar Pradesh [169]. Although sugarcane bagasse is abundant, a large portion is discarded or burned in open fields, resulting in significant environmental pollution, including increased particulate matter, carbon emissions, and greenhouse gases [10]. These improper disposal practices contribute to air pollution and climate change, posing health risks to human populations, particularly in rural and semi-urban areas. Recycling and adding value to SG through sustainable and environmentally friendly methods has become an urgent necessity. In recent years, researchers and industries have explored a variety of applications for sugarcane bagasse due to its lignocellulosic composition and high carbon content. It has been utilized in the paper and pulp industry, bio-composite manufacturing, fertilizers, animal feed, bioplastics, and for extracting bioethanol. D. Suhardy et al.[170] developed alternative paper products using sugarcane bagasse (SG), reporting that its carbon and silica content were around 90%

and 10%, respectively, which is significantly higher than that of other agro-wastes like rice straw. Azevedo and Galiana [171] developed a method for extracting ethanol from sugarcane bagasse in Brazil, emphasizing its importance in the production of bioelectricity and clean fuels. These advancements illustrate the potential of sugarcane bagasse as a renewable, low-cost, and biodegradable raw material for various industrial applications. Microwave absorption has recently increased in significant interest among the many emerging applications of sugarcane bagasse. This is mainly due to the high carbon content of sugarcane bagasse, which plays an important role in the attenuation of EM waves. In the context of EMI shielding and radar absorption, materials with high dielectric and conductive properties are crucial [172]. SG materials show these characteristics due to their porous carbonaceous matrix, which improves electromagnetic interaction. The porous structure and high surface area of SG-derived carbon facilitate effective absorption and scattering of electromagnetic waves. Moreover, the carbon atoms transform incoming microwave energy into thermal energy in form of heat[5] . This energy transformation happens when the alternating electric field generated by microwave radiation causes charge carriers to oscillate. This leads to both dielectric and conductive losses that contribute to energy dissipation. Furthermore, carbon-based materials demonstrate excellent broadband absorption, chemical stability, low density, and environmental friendliness. These traits make them excellent candidates for use as microwave absorber materials (MAMs). Using SG in this area not only helps manage environmental waste but also contributes to the making of sustainable and cost-effective MAMs. These materials are gradually needed for applications such as radar systems, telecommunication devices, stealth technology, and shielding enclosures for electronic circuits. To improve microwave absorption efficiency of SG, it can be combined with conductive nanomaterials such as multiwalled carbon nanotubes (MWCNTs). MWCNTs improve the dielectric properties and electrical conductivity of the composite, enhancing impedance matching and microwave absorption [173]. The combination of the porous SG and high aspect ratio of MWCNTs enables multiple reflections, interfacial polarization, and effective energy attenuation.

In this chapter, the focus is on the development and analysis of a composite made from sugarcane bagasse with multiwalled carbon nanotubes (MWCNTs). The microwave absorption of these composites was evaluated in the X-band (8.2–12.4 GHz) frequency range. Various parameters were analytically studied, including dielectric properties, dielectric loss tangent, conductivity, reflection loss, and absorption percentage, to measure the material's potential as a microwave absorber. The goal is to evaluate the SG-MWCNT composite's effectiveness in

absorbing microwaves and emphasize its potential as an eco-friendly, cost-effective, and sustainable solution for electromagnetic wave attenuation.

5.2. Microwave Absorber Sample Fabrication Method for SG-MWCNT Composites

In this chapter, a series of four rectangular microwave absorber samples was developed with different thicknesses and made from a novel bio-composite material. This material is formulated by integrating MWCNTs with sugarcane bagasse (SG). The systematic and methodical approach used for fabricating these SG-MWCNTs composite absorber samples is illustrated in Figure. 5.1, which outlines the complete step-by-step workflow from raw material collection to the final fabrication of the absorber.

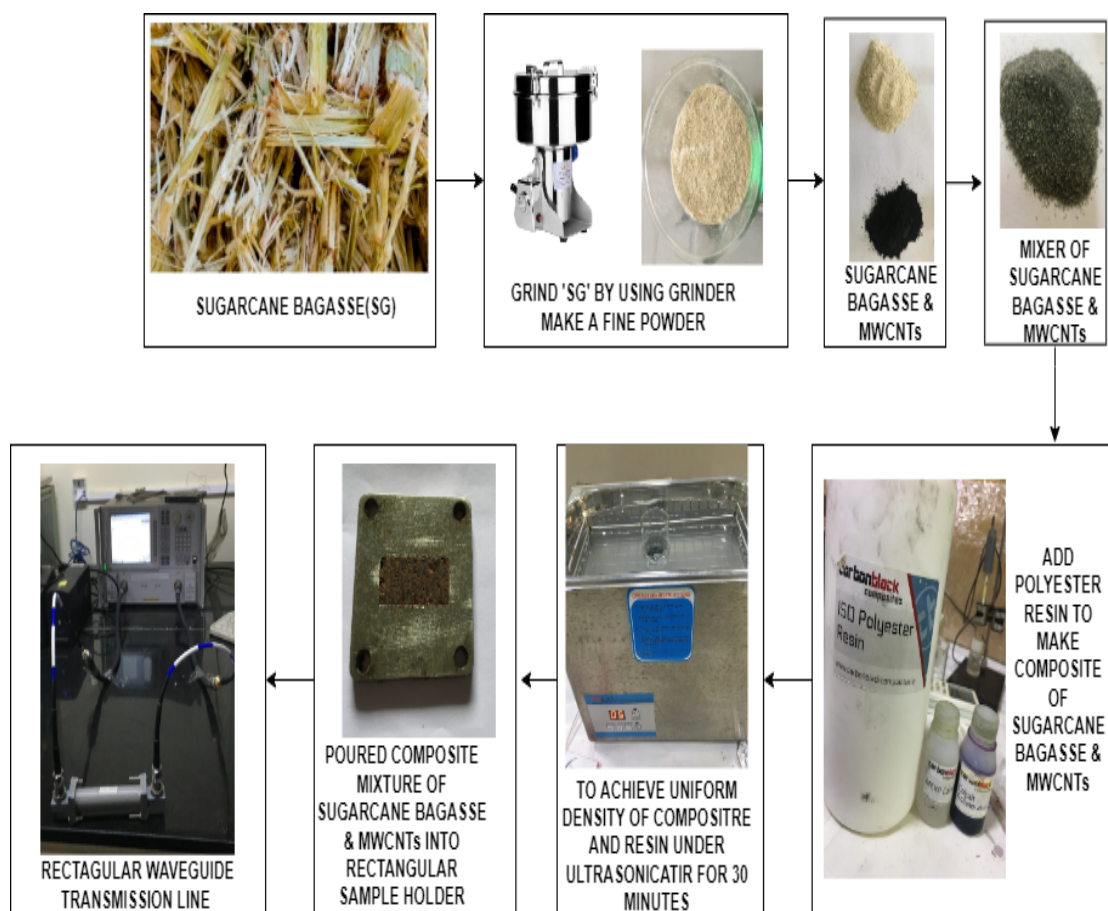


Figure 5.1. Preparation Procedure of Sugarcane Bagasse-MWCNT Composite Microwave Absorbers

The process began with the collection of raw sugarcane bagasse, a fibrous waste material produced after extracting juice from sugarcane during sugar production. In this study, the sugarcane bagasse was collected from a sugar factory in Patiala, Punjab. This location was selected due to the large quantities of sugarcane processed there, resulting in an abundance of bagasse as a by-product. After collecting the bagasse, it was spread out in direct sunlight and

left to dry naturally for approximately 25 to 30 days. The extended period of sun drying effectively removed the moisture content from the bagasse. This natural drying process also reduced the risk of fungus or bacteria developing on the material. Consequently, the bagasse became dry, clean, and ready for the subsequent steps in preparing the microwave absorber samples. After sufficient drying, the sugarcane bagasse was ground using a high-speed mechanical grinder. The purpose of this step was to break down the bulk sugarcane bagasse into smaller fragments. The resulting ground material was then passed through a sieve to obtain a fine powder made up of microscopic particles, although it remained somewhat non-uniform. This sieving process is crucial for achieving better consistency in dispersion during the preparation of composites. Figure 5.2 provides a visual representation of powdered SG alongside the multi-walled carbon nanotubes (MWCNTs) used in the fabrication process. The MWCNTs have a purity of 97% and a diameter ranging from 5 to 20 nm.



Figure 5.2 SG and MWCNTs in powder form

After preparing the powder, the next step in synthesizing the composite involved embedding the powdered SG and multi-walled carbon nanotubes (MWCNTs) into a polyester resin matrix. Polyester resin was chosen for its relatively low cost, easy availability, and compatibility with carbon-based fillers. The powdered sugarcane bagasse and MWCNTs were mixed homogeneously into the resin. To achieve a uniform dispersion of the MWCNTs and prevent agglomeration, an issue often encountered with nanomaterials, the mixture underwent ultrasonic treatment for 30 minutes using an ultrasonicator. This sonication process helps to break apart clumps and promotes effective interaction between the carbon nanotubes and the bio-based sugarcane bagasse matrix, thereby enhancing the overall uniformity and mechanical strength of the composite. After ultrasonication, MEKP was added to the composite mixture as

a curing agent. Cobalt naphthenate was included as an accelerator to promote the polymerization of the resin. The choice of MEKP and cobalt was based on their established effectiveness in facilitating efficient curing at room temperature. To ensure consistent curing behaviour and mechanical strength, the weight ratio of polyester resin to MEKP was carefully maintained at 5:1 across all samples. Various resins, such as polyurethane, urea-formaldehyde, and phenol-formaldehyde, have been studied in the literature for their use in microwave absorber fabrication. However, their widespread adoption is limited due to environmental and health concerns, primarily because they are toxic and non-biodegradable. In contrast, polyester resin and methyl ethyl ketone peroxide (MEKP) are considered more environmentally sustainable alternatives. Additionally, the United States Department of Agriculture (USDA) has approved the use of polyester resins and MEKP in the production of food-grade containers, highlighting their relative safety and ecological compatibility. These substances also function as effective binding agents, providing high resistance to abrasion and preventing air gaps within the composite structure, an important aspect for achieving efficient microwave absorption. After preparing the composite mixture, it was quickly poured into a pre-fabricated rectangular aluminum mold with dimensions of 22.860 mm × 10.160 mm × 3 mm. The mold design adheres to standard dimensions used in waveguide-based microwave measurement systems, enabling reliable and reproducible testing of the fabricated absorber samples. The fabrication process was carried out for four distinct samples; each prepared with different thicknesses and varying loadings of multi-walled carbon nanotubes (MWCNTs). This variation was done to investigate how these parameters affect microwave absorption behaviour. Table 5.1 includes detailed information on the composition, weight of the components used, and dimensions of each fabricated sample.

Table 5.1 Fabrication of the sample and its dimensions

Samples	Amount of sugarcane Bagasse (gm)	polyester resin and hardener (gm)	Added MWCNTs		Dimensions of mould (mm)	Thickness of samples (mm)
			(gm)	wt. %		
S1(1wt%CNTs+SG with 3mm thick)	2	3	0.05	1	22.860×10.160×3	3
S2(1wt%CNTs+SG with 4mm thick)			0.05	1	22.860×10.160×4	4
S3 (3wt%CNTs + SG with 3mm thick)			0.15	3	22.860×10.160×3	3
S4 (3wt%CNTs + SG with 4mm thick)			0.15	3	22.860×10.160×4	4

These samples were later assessed for their electromagnetic wave absorption capabilities within the X-band frequency range. Their dielectric properties, interfacial characteristics, and structural integrity under microwave exposure are discussed in the following sections of this chapter.

5.3 Measurement Setup for Electromagnetic Analysis

5.3.1 Thickness measurement

The thickness of the absorber sample is essential for its microwave absorption performance, as variations in thickness can significantly influence the material's dielectric properties. Accurate measurement of the thickness of each rectangular composite sample is vital for ensuring consistency and reliability in experimental analyses. In this proposed work, a digital electronic caliper was utilized to measure the thickness of fabricated SG-MWCNTs composite samples with high precision, as illustrated in Figure 5.3. The caliper provides digital readouts in millimeters, enabling precise and repeatable measurements of thickness.



Figure.5.3 A Digital caliper is used for the measurement of sample thickness.

5.3.2 Particle size measurements

A material's particle size greatly influences its electromagnetic absorption behaviour [5]. In this proposed work, where sugarcane bagasse (SG) serves as the base material for composite microwave absorbers, understanding and evaluating particle size distribution is essential. Particle size influences various material characteristics, including surface area, porosity, interfacial polarization, and ultimately the material's capacity to attenuate incident electromagnetic radiation [174]. Hence, precise characterization of particle size is crucial for linking microstructural properties with dielectric behaviour and microwave absorption efficiency. To measure the particle size of ground sugarcane bagasse powder, an optical microscope with a 50× optical zoom lens was used. This magnification facilitates the detailed

visualization of micro-sized particles and aids in evaluating the uniformity of size and morphology. Figure 5.4 presents (a) the optical microscope employed for particle size analysis, (b) the microscopic image displaying the morphology of sugarcane bagasse (SG) particles, and (c) the estimated dimensions of individual particles captured under magnification. The SG powder was produced by grinding sun-dried bagasse with a mechanical grinder, followed by sieving to separate the fine particles from larger aggregates. Due to the limitations of mechanical grinding, the particle sizes produced were not uniform. Despite the sieving process, the particles showed a broad size distribution, ranging from approximately 95 μm to 580 μm , as observed in the microscope image. This variation is commonly observed in organic fibrous materials when traditional grinding techniques are employed. The impact of particle size on microwave absorption is especially important. Smaller particles exhibit higher surface area-to-volume ratios, placing more atoms on their surface [175]. This increased surface area enhances interfacial polarization, which is crucial for dielectric loss mechanisms. Furthermore, finer particles with a porous structure can cause multiple scattering and reflections of electromagnetic waves within the material, thereby improving absorption capabilities.

The relationship between the specific surface area, A_s and r is particle radius is mathematically expressed as equation (5.1):

$$A_s \propto \frac{1}{r} \quad (5.1)$$

This equation indicates that specific surface area is inversely proportional to particle radius; smaller particles offer a larger surface area, enhancing interactions with microwave radiation [175].

In this proposed study, the sugarcane bagasse powder was discovered to be highly porous, lightweight, and structurally irregular, which are ideal characteristics for a material intended for microwave absorption applications. The enhanced porosity and surface roughness create more pathways for polarization and energy dissipation mechanisms, making the particle size distribution of SG a key factor in optimizing the electromagnetic performance of the SG-MWCNTs composite absorber.

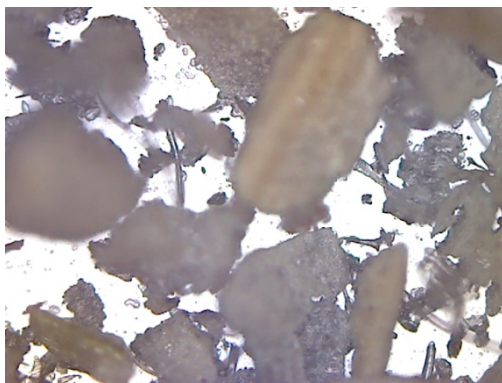
5.3.3 Dielectric properties measurement

Accurate evaluation of a microwave absorber's dielectric properties involves using standard measurement techniques, selected according to the material's type, shape, and operating frequency range. Commonly used techniques include the open-ended coaxial probe method,

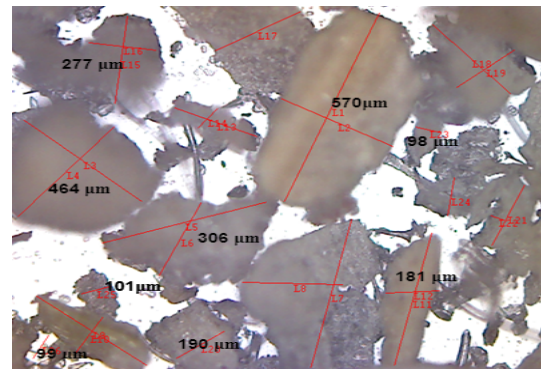
the rectangular waveguide transmission line method, and the dielectric probe technique. Each method provides distinct advantages in terms of sensitivity, bandwidth, and sample configuration.



a



b



c

Figure 5.4 presents (a) the optical microscope employed for particle size analysis, (b) the microscopic image displaying the morphology of sugarcane bagasse (SG) particles, and (c) the estimated dimensions of individual particles captured under magnification.

In this proposed study, the rectangular waveguide transmission line method was selected as the most appropriate approach to characterize the dielectric properties of a composite material made from sugarcane bagasse (SG) and multi-walled carbon nanotubes (MWCNTs) (referred to as SG-MWCNTs) within the X-band frequency range of 8.0 to 12.4 GHz. This waveguide-based technique was chosen for its high accuracy in measuring dielectric constants and loss factors, particularly for solid rectangular samples that can be accurately inserted into the waveguide cavity. The experimental setup includes a WR-90 rectangular waveguide connected to a Vector Network Analyzer (VNA) via two high-frequency coaxial cables. The VNA functions in two-port mode to capture scattering parameters (S-parameters), specifically S_{11} (reflection coefficient) and S_{21} (transmission coefficient), which are used to determine the

1 dielectric properties of the test samples. Figure 5.5 provides an overview of the complete experimental setup. In Figure 5.5(a), the VNA and the waveguide configuration utilized for dielectric measurements are shown. Figure 5.5(b) displays the fabricated sample of SG-MWCNTs that was used for testing. Meanwhile, Figure 5.5(c) presents the rectangular mold filled with the composite material, which was designed to ensure that the dimensions precisely match the internal dimensions of the WR-90 waveguide.

8 Before conducting actual measurements, it is crucial to calibrate the Vector Network Analyzer. Calibration is essential to remove systematic errors caused by connectors, cables, and especially by any air gaps that may exist between the sample and the waveguide flanges. An empty WR-90 waveguide section filled with air is inserted between the VNA ports to conduct this calibration. 1 The dielectric constant of air is set to its theoretical value of 1, which allows the system to establish a reference baseline for future measurements. After successfully completing the calibration process, the SG-MWCNTs composite sample, fabricated in a rectangular shape that fits perfectly into the WR-90 waveguide (with a cross-section of 22.86 mm × 10.16 mm), is carefully placed into the waveguide cavity. It is crucial that the sample fits tightly, with no air gaps or misalignment, to ensure accurate interaction with electromagnetic waves and to avoid any measurement artifacts. During testing, the Vector Network Analyzer (VNA) records the S-parameters as electromagnetic waves propagate through and reflect off the sample. These recorded parameters are then processed to compute the real part (ϵ') and the imaginary part (ϵ'') of the complex permittivity. 19 The real part represents the material's ability to store electrical energy, while the imaginary part indicates its capacity to dissipate energy. These dielectric parameters provide valuable insights into the electromagnetic behaviour of the SG-MWCNTs composite and its potential effectiveness as a microwave absorber. 4 Dielectric measurements were conducted across the entire X-band range (8.0–12.4 GHz) to capture variations in the material's electromagnetic response based on frequency. 7 The collected data were analyzed to assess how the addition of multi-walled carbon nanotubes (MWCNTs) and changes in sample thickness affect the dielectric constant and loss tangent. These two parameters are crucial indicators of microwave absorption performance.

5.4 Analysis of Experimental Outcomes

5.4.1 Carbon composition of Sugarcane Bagasse

68 The carbon content of sugarcane bagasse, a crucial factor in assessing its suitability for microwave absorption applications, was analyzed using a CHNS elemental analyzer. This analytical technique is commonly utilized in materials science and environmental studies to

identify and quantify the presence of four essential elements: Carbon (C), Hydrogen (H), Nitrogen (N), and Sulphur (S). The instrument works by burning a specific mass of the sample at high temperatures and then analyzing the gases produced using thermal conductivity detectors or infrared sensors. The quantitative results provide essential insights into the elemental composition of organic and polymeric materials

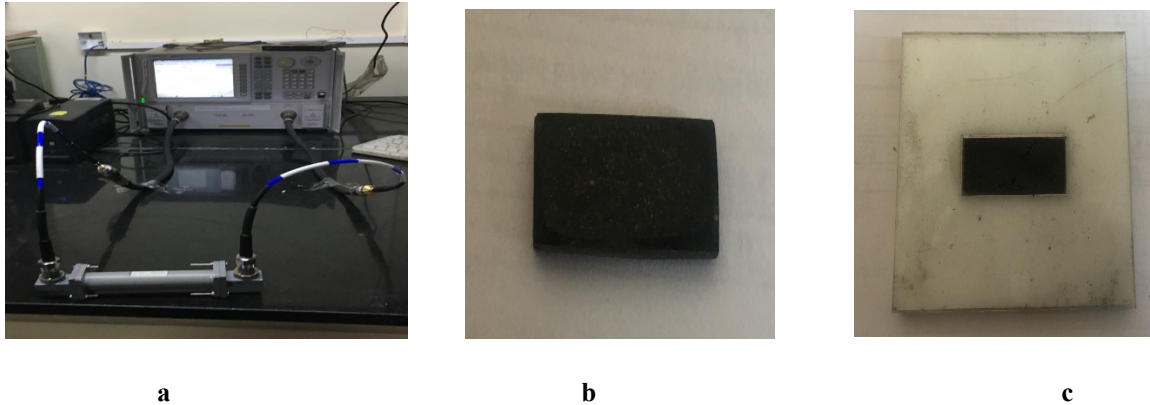


Figure 5.5. The **a** Measurement set up of rectangular waveguide transmission line, **b** SG-MWCNTs sample, and **c** rectangular mould with SG-MWCNTs sample.

In this proposed study, the CHNS analysis was performed to evaluate the carbon-rich composition of sugarcane bagasse. Carbon is crucial for the attenuation of electromagnetic waves. Materials with a higher carbon content are typically linked to enhanced dielectric loss and conductivity, making them promising candidates for use as microwave absorbers.

The results of the CHNS elemental analysis are shown in Table 5.2. The data clearly indicate that sugarcane bagasse has a notable carbon content of 37.34%, which underlies its electromagnetic response characteristics. Additionally, the material contains 6.44% hydrogen and 0.62% nitrogen. While sulphur was found to be negligible or below the detection limit of the instrument, this is desirable because sulphur-containing compounds can contribute to undesirable chemical reactivity or emissions during thermal processing.

Table 5.2 CHNS Elemental analysis of agricultural waste materials

Elements	Sugarcane Bagasse
Carbon	37.34%
Hydrogen	6.44%
Nitrogen	0.62%
Sulphur	-

The relatively high carbon content of sugarcane bagasse indicates that it contains a significant amount of organic carbon-based compounds, including cellulose, hemicellulose, and lignin.

These structural polymers are not only thermally stable but also contribute to the material's intrinsic dielectric properties. The presence of carbon makes sugarcane bagasse a suitable candidate for combining with conductive fillers, such as multi-walled carbon nanotubes (MWCNTs), to enhance its microwave absorption capabilities.

Therefore, the CHNS analysis confirms that sugarcane bagasse is an ideal bio-based carbon source for creating lightweight, cost-effective, and environmentally friendly microwave absorber composites.

5.4.2 Dielectric Properties of SG-MWCNTs Composites

Evaluating the dielectric properties of microwave absorbing materials (MAMs) is vital, as they specifically affect the material's interaction with electromagnetic waves. Dielectric properties refer to a material's capacity to store electromagnetic energy, changeover it into thermal energy, and scatter that energy as heat. This inherent conduct decides how much incident microwave energy is reduced inside the absorber structure.

In this proposed investigation, the dielectric properties of four sugarcane bagasse (SG)-based composite samples incorporated with multi-walled carbon nanotubes (MWCNTs) were measured. The samples are designated as S1, S2, S3, and S4. The samples vary in both filler content (weight percent) and physical thickness. Samples S1 and S2 contain 1 wt.% multi-walled carbon nanotubes (MWCNTs), with thicknesses of 3 mm and 4 mm, respectively. In contrast, samples S3 and S4 contain 3 wt.% MWCNTs, with the same respective thicknesses of 3 mm and 4 mm.

The dielectric properties, including the dielectric constant (ϵ') and the dielectric loss factor (ϵ''), were measured using the rectangular waveguide method over the X-band frequency range of 8.0 to 12.4 GHz. The results are presented in Tables 5.3 and 5.4, which compare the performance across different weight percentages of multi-walled carbon nanotubes (MWCNT) and varying thickness configurations.

Table 5.3 Dielectric constants, ϵ' for different SG-MWCNTs samples over the frequency range of 8-12.4 GHz

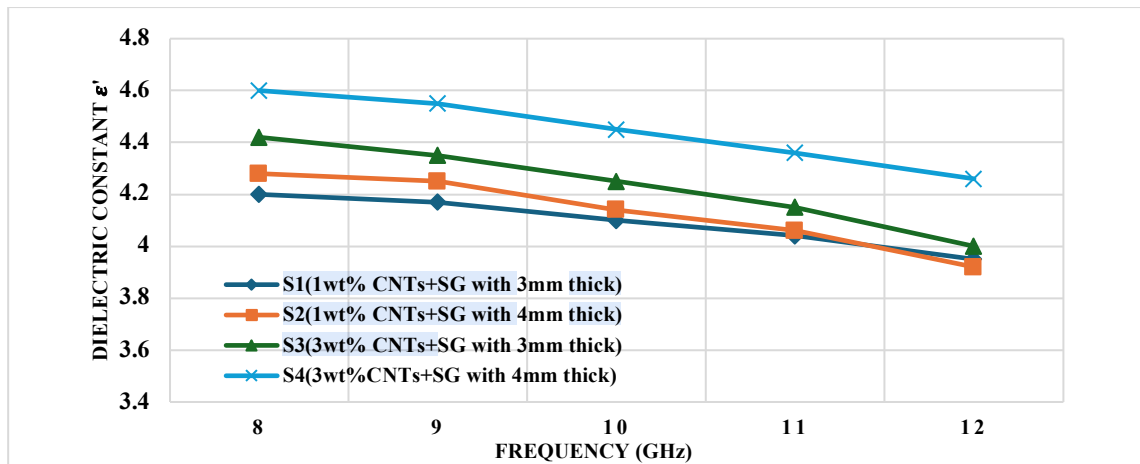
Samples	Composite Materials	Thickness (mm)	Dielectric constant (ϵ') value at 8-12.4 GHz Frequency				
			8	9	10	11	12
S1	Sugarcane bagasse + 1 wt.% MWCNTs	3	4.209	4.178	4.102	4.04	3.953

S2	Sugarcane bagasse + 1wt.% MWCNTs	4	4.283	4.251	4.141	4.06	3.925
S3	Sugarcane bagasse + 3wt.% MWCNTs	3	4.427	4.357	4.259	4.159	4.007
S4	Sugarcane bagasse + 3wt.% MWCNTs	4	4.6	4.551	4.453	4.364	4.265

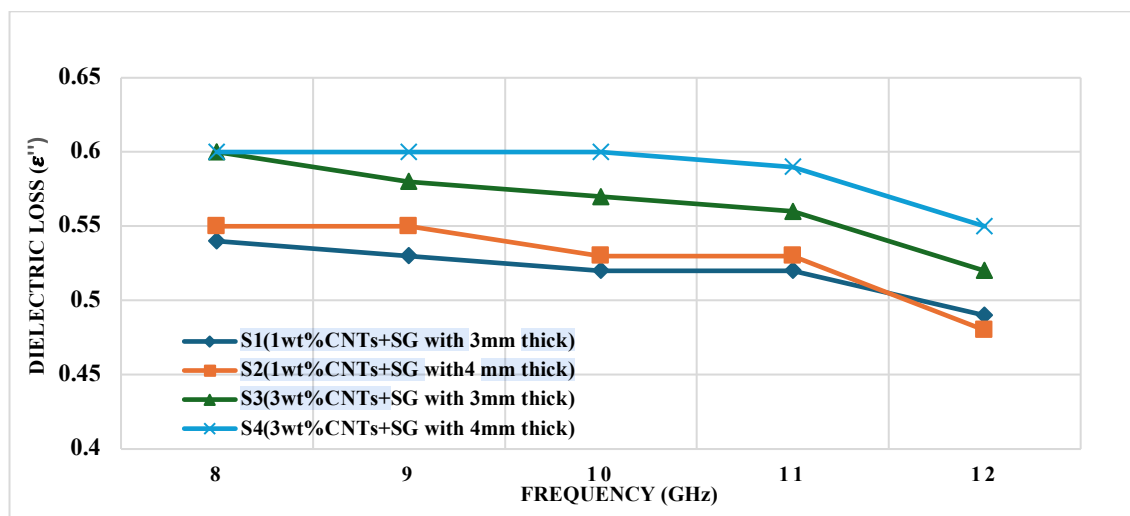
Table 5.4 Loss factor, ϵ'' for different SG-MWCNTs samples over the frequency range of 8-12.4 GHz

Samples	Composite Materials	Thickness (mm)	Dielectric loss (ϵ'') value at 8-12.4 GHz Frequency				
			8	9	10	11	12
S1	Sugarcane bagasse + 1wt.% MWCNTs	3	0.546	0.537	0.52	0.526	0.496
S2	Sugarcane bagasse + 1wt.% MWCNTs	4	0.558	0.551	0.537	0.533	0.487
S3	Sugarcane bagasse + 3wt.% MWCNTs	3	0.605	0.589	0.578	0.567	0.521
S4	Sugarcane bagasse + 3wt.% MWCNTs	4	0.605	0.6	0.605	0.592	0.552

A significant trend in the data shows that both the dielectric constant and dielectric loss increase with (a) higher filler concentrations of MWCNTs and (b) greater sample thickness. This enhancement is due to the improved conductive pathways established by the MWCNT network within the SG matrix, which increases the material's capacity to interact with and attenuate electromagnetic radiation. Additional insights can be gained from Figures 5.6(a) and (b), which illustrate the variation in the dielectric constant and loss factor as a function of frequency. A decreasing trend in dielectric loss (ϵ'') was observed as frequency increased for all samples. This behaviour is due to a decrease in dipolar polarization at higher frequencies. Inertial, elastic, and repulsive forces can impede the rotation of electric dipoles. As a result, this leads to volumetric heating and dielectric loss caused by internal friction among the dipoles, which contributes to energy dissipation within the material. The dielectric loss factor of sample S1 (1 wt.% MWCNTs) decreases from 0.52 at 8 GHz to 0.49 at 12 GHz, illustrating its frequency dependence.



a



b

Fig.5.6 The **a** dielectric constant ϵ' , and **b** loss factor ϵ'' values of fabricated four composite samples of SG-MWCNTs measured with a dielectric probe.

Table 5.5 The average values of dielectric properties of SG-MWCNTs samples in the frequency range 8.2-12.4 GHz.

Parameters	Samples			
	S1 (1wt.%CNTs+SG with 3mm thickness)	S2 (1wt.%CNTs+SG with 4mm thickness)	S3 (3wt.%CNTs+SG with 3mm thickness)	S4 (3wt.%CNTs+SG with 4mm thickness)
ϵ'	4.09	4.13	4.24	4.44
ϵ''	0.52	0.53	0.57	0.59
$\tan \delta$	0.12	0.12	0.13	0.13

σ (S/m)	0.24	0.24	0.26	0.26
D(mm)	0.042	0.042	0.040	0.036

Table 5.5 provides a detailed overview of the average dielectric parameters for four bio composite samples made from sugarcane bagasse (SG) combined with multi-walled carbon nanotubes (MWCNTs). These parameters were measured across the X-band frequency range of 8.2 to 12.4 GHz. The samples, labeled S1 through S4, were produced by varying both the weight percentage of MWCNTs and the thickness of the composites to investigate how these factors affect the material's dielectric response. Specifically, S1 and S2 contain 1 wt.% MWCNTs, with thicknesses of 3 mm and 4 mm, respectively, while S3 and S4 have 3 wt.% MWCNTs, also with thicknesses of 3 mm and 4 mm.

The real part of the dielectric constant (ϵ'), which indicates the material's ability to store electrical energy in an alternating electromagnetic field, shows a steady increase across the four samples. The ϵ' value rises from 4.09 in S1 to 4.44 in S4, indicating that higher filler loading and increased sample thickness both positively influence the material's polarization behaviour. This increase in ϵ' with higher MWCNT content is due to the high aspect ratio and polarizability of carbon nanotubes, which enhance interfacial polarization and improve dipole alignment in response to the electric field. The slight increase in ϵ' from S1 to S2, with a constant filler content but increased thickness, indicates that a thicker medium provides a longer propagation path for electromagnetic waves, allowing for greater interaction and energy storage.

The imaginary part of the dielectric constant (ϵ''), known as the dielectric loss factor, indicates the energy lost as heat due to polarization lag and conduction processes. The ϵ'' value increases steadily from 0.52 in S1 to 0.59 in S4, primarily due to the enhanced conduction pathways created by the increased MWCNT network within the sugarcane bagasse. As the carbon content increases from 1 wt.% to 3 wt.%, a greater number of interfacial regions and conductive channels are formed, leading to enhanced energy dissipation resulting from both interfacial polarization and conductive losses. Sample S2, which has greater thickness than S1 but the same MWCNT content, exhibits a slightly higher loss factor (0.53 compared to 0.52). This suggests that increased sample thickness enhances dielectric loss to a limited yet significant extent. The loss tangent ($\tan \delta$), defined as the ratio of ϵ'' to ϵ' , offers a comprehensive measure of the material's energy storage and loss capabilities. The $\tan \delta$ values for samples S1 and S2 are 0.12, while for S3 and S4, they are 0.13. Though the increase is modest, it signifies enhanced dielectric performance regarding energy dissipation at higher filler content. A higher

loss tangent usually indicates improved microwave attenuation efficiency, suggesting that samples S3 and S4 have a better balance of permittivity and loss characteristics, making them suitable for effectively absorbing electromagnetic energy. The electrical conductivity (σ) of the composites, which affects the conduction loss component of the dielectric behaviour, increases from 0.24 S/m for samples S1 and S2 to 0.26 S/m for samples S3 and S4. This trend corresponds with the anticipated result that higher MWCNT content promotes the establishment of continuous or semi-continuous conductive networks within the matrix, thus enhancing charge transport. These networks enable a more efficient conversion of electromagnetic energy into thermal energy through ohmic loss mechanisms. The observation that conductivity remains constant within pairs of samples with identical multi-walled carbon nanotube (MWCNT) content (for example, S1 vs. S2 and S3 vs. S4) further confirms that the amount of filler loading is the primary factor influencing conductivity, while the thickness of the samples plays a secondary role.

Finally, skin depth (D) refers to the depth at which microwave energy decreases to 37% of its surface value; this depth is inversely related to both frequency and conductivity. A smaller skin depth indicates stronger attenuation and more effective confinement of electromagnetic energy near the material's surface. The skin depth slightly decreases from 0.042 mm in samples S1 and S2 to 0.036 mm in sample S4. This reduction aligns with the increased conductivity and loss factor, emphasizing the improved energy absorption capability of the material with a higher carbon nanotube content. A lower skin depth results in more rapid absorption of microwave energy, leading to improved attenuation characteristics over a shorter distance.

In summary, the data presented in Table 5.4 clearly illustrates that incorporating multi-walled carbon nanotubes (MWCNTs) into sugarcane bagasse significantly enhances the dielectric properties of the composite materials. Both the real and imaginary components of the dielectric constant, along with electrical conductivity and loss tangent, show positive correlations with increased filler loading. Sample S4, which contains 3 wt.% MWCNTs at a thickness of 4 mm, demonstrates the highest values for dielectric constant, loss factor, conductivity, and the lowest skin depth, making it the most effective configuration for electromagnetic wave attenuation. This confirms that optimizing the conductive filler content and structural thickness of biowaste-based composites is an effective strategy for enhancing their performance as sustainable and cost-efficient microwave absorbers.

5.4.3 Percentage Error Analysis and Standard Deviation of Dielectric Parameters

To evaluate the accuracy and consistency of the dielectric measurements for the four composite samples (S1, S2, S3, and S4), we calculated the percentage error and standard deviation for each parameter: dielectric constant (ϵ'), loss factor (ϵ'') to tangent loss ($\tan \delta$), and electrical conductivity (σ).

The percentage error indicates how much the measured values vary in relation to their average. It offers a quantitative measure of uncertainty or dispersion within the data. This metric helps assess the range of variation in experimental data and identifies which parameters exhibit greater measurement variability. To perform a percentage error analysis, use the following equation (5.2):

$$\text{Percentage Error}(\%) = \left(\frac{\text{Maximum value} - \text{Minimum value}}{\text{Average value}} \right) \times 100 \quad (5.2)$$

Table 5.5 presents a statistical evaluation of the dielectric parameters: dielectric constant (ϵ'), loss factor (ϵ''), tangent loss ($\tan \delta$), and electrical conductivity (σ), measured across four composite samples (S1, S2, S3, and S4). The percentage error measures the relative variation of observed values compared to their average, providing insight into the data's distribution across samples. Among the listed parameters, the loss factor (ϵ'') shows the highest percentage error at 13.4%, indicating greater variability, likely due to the sensitivity of measuring energy dissipation within the composites. The dielectric constant (ϵ') has a moderate error of 8.5%, while both tangent loss ($\tan \delta$) and electrical conductivity (σ) exhibit lower percentage errors of 8.3%, indicating more consistent behavior among these properties.

In addition to percentage error, standard deviation (s) is used to evaluate the consistency and repeatability of measurements. A smaller standard deviation indicates that the data points are closely clustered around the mean, reflecting reliable experimental outcomes. Standard deviation is a statistical measure that shows how much a set of values varies from their mean. A lower standard deviation indicates that the values are closely grouped together, reflecting more precise measurements. To perform a Standard deviation analysis, use the following equation (5.3):

$$s = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (5.3)$$

Where s is the standard deviation, x_i is each individual measurement, $\bar{x}$ is the mean of the measurement, and n is the number of measurements. Table 5.6 presents the Standard deviation of parameters dielectric parameters: dielectric constant (ϵ') loss factor (ϵ'') tangent loss ($\tan \delta$),

and electrical conductivity (σ), measured across four composite samples (S1, S2, S3, and S4) exhibit low standard deviation values: 0.156 for ϵ' , 0.033 for ϵ'' , 0.005 for $\tan \delta$, and 0.011 for σ . This indicates a high level of reproducibility in the measured dielectric properties across the samples. Although some variability is present, especially in the loss factor, the experimental results are generally stable and reliable.

Table 5.6. The % error analysis and Standard deviations of the dielectric constant, loss factor, tangent loss and conductivity of four composite samples S1, S2, S3, S4

Parameters	S1	S2	S3	S4	% error analysis	Standard deviations (s)
Dielectric constant (ϵ')	4.09	4.13	4.24	4.44	8.5	0.156
Loss factor (ϵ'')	0.52	0.53	0.57	0.59	13.4	0.033
Tangent loss ($\tan \delta$)	0.12	0.12	0.13	0.13	8.3	0.005
Electrical Conductivity ($\sigma, S/m$)	0.24	0.24	0.26	0.26	8.3	0.011

5.4.4 Microwave Absorption Performance Analysis of Sugarcane Bagasse/MWCNT Composites

After evaluating the dielectric properties of all sugarcane bagasse (SG) and multi-walled carbon nanotube (MWCNT)-based biocomposite samples, specifically S1, S2, S3, and S4, their microwave absorption behaviour was thoroughly analyzed. This analysis aimed to understand how these composites interact with incident electromagnetic waves, specifically regarding reflection loss and overall absorption efficiency. In this proposed study, a typical configuration was used to evaluate the microwave absorption performance, where one side of each composite sample was backed with a perfect electric conductor (PEC), as shown in Figure 5.7. This PEC backing is vital for experimental measurements as it entirely blocks wave transmission through the sample. Consequently, the transmission coefficient S_{21} becomes zero, and we measure the reflection coefficient S_{11} . This condition ensures that the incident wave is either absorbed by the sample or reflected back, with no energy passing through the material. This simplifies the calculation of microwave absorption performance.

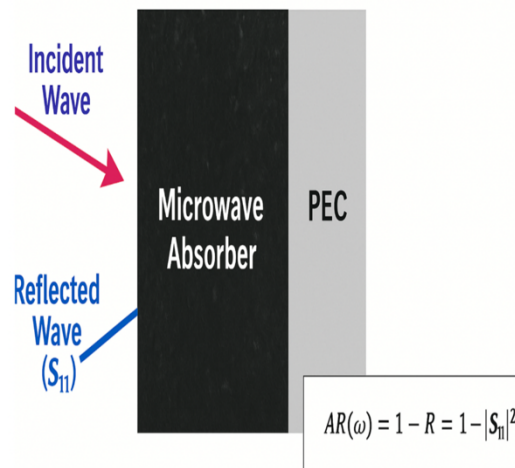


Figure 5.7 Schematic representation of Microwave absorber With PEC backing, eliminating transmission and enabling absorption calculation solely from reflection

Reflection loss, which quantifies the amount of electromagnetic energy reflected from a material's surface, was calculated using Equation (3.10). In parallel, the absorption percentage was calculated using Equation (3.13). This equation correlates the RL value with the amount of electromagnetic energy absorbed by the material, thus offering a clearer understanding of the absorber's efficiency.

Reflection loss values were calculated for all composite samples across the X-band frequency range (8.2–12.4 GHz) using the dielectric parameters. The results indicated a strong dependence of the absorption behaviour on both the content of MWCNTs and the sample's thickness. Among the four samples, S4, which contained 3 wt.% MWCNTs with a thickness of 4 mm, demonstrated the most promising performance. It achieved a minimum reflection loss of -22.8 dB at 8.8 GHz, indicating that nearly 99.4% of the incident electromagnetic energy was absorbed. This excellent performance can be attributed to several key factors. Firstly, increasing the content of MWCNT enhances the dielectric and conductive losses of the composite. The presence of well-dispersed MWCNTs provides additional conduction pathways for charge carriers and increases interfacial polarization, both of which significantly contribute to electromagnetic energy dissipation. Dipolar polarization effects occur when polar molecules align themselves in response to an applied electric field. These effects are more pronounced at lower frequencies because the dipoles have sufficient time to align with the field. As a result, this alignment leads to higher dielectric loss and enhanced energy absorption. As frequency increases, dipoles struggle to realign with the oscillating field, resulting in diminished net polarization and a gradual reduction in reflection loss at higher frequencies.

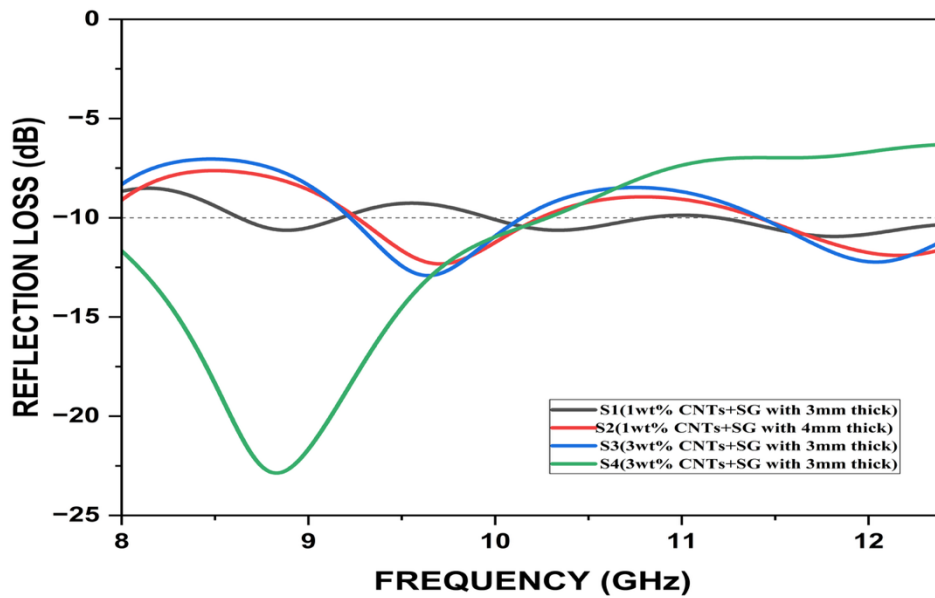


Figure 5.8 Frequency-dependent reflection loss plot of SG-MWCNT composite samples over X-band.

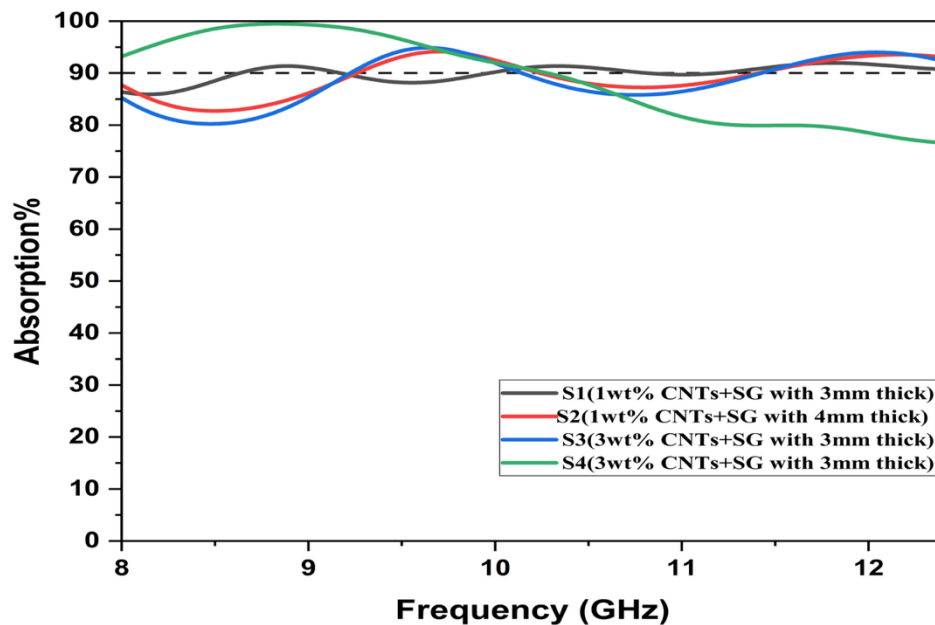


Figure 5.9 Microwave absorption characteristics of SG-MWCNT composite samples over X-band.

The other composite samples also demonstrated acceptable absorption performance. Sample S3, which contained 3 wt.% MWCNTs and had a thickness of 3 mm, recorded a minimum reflection loss (RL) of -12.9 dB, indicating an absorption efficiency of over 95%. Sample S2, comprised of 1 wt.% MWCNTs at a thickness of 4 mm, showed a minimum RL of -12.3 dB,

confirming its ability to attenuate more than 95% of the incident wave. Even Sample S1, with the lowest MWCNT loading of 1 wt.% and a thickness of 3 mm, achieved a reflection loss of -10.6 dB, which meets the commonly accepted minimum threshold for microwave absorbers ($RL \leq -10$ dB), corresponding to over 90% wave attenuation. These results indicate that all four composite formulations are viable candidates for microwave absorption applications, as increasing the MWCNT content and sample thickness enhances performance.

In addition to the RL analysis, absorption percentage results were calculated to provide a clearer understanding of energy dissipation across the samples. As anticipated, the sample with the highest reflection loss, S4, demonstrated the maximum absorption, reaching nearly 99.4%. Similarly, both S3 and S2 exhibited absorption levels exceeding 95%. Although S1 was the least efficient of the four samples, it still managed to absorb more than 90% of the incident microwave energy. These results highlight the significant potential of SG-MWCNT composites as high-performance materials for electromagnetic wave attenuation. The detailed data, including reflection loss values and the corresponding frequencies at which peak performance was achieved, are presented in Table 5.7.

Table 5.7 Maximum reflection loss of SG-MWCNTs composite samples

Samples	Reflection loss (dB)	RL <-10 dB at frequency (GHz)
S1	-10.6	8.9
S2	-12.3	9.7
S3	-12.9	9.6
S4	-22.8	8.8

Additionally, Sample S4 demonstrated excellent dielectric properties, featuring a dielectric constant (ϵ') of 4.4, a loss tangent of 0.131, and a broad -10 dB bandwidth of 2.2 GHz. This broad bandwidth shows that the material effectively absorbs across various frequencies, which is essential for practical applications. These observations highlight the combined effects of incorporating multi-walled carbon nanotubes (MWCNT) and optimizing sample thickness on the absorption of electromagnetic waves. The enhancements in reflection loss (RL) and absorption efficiency primarily result from the creation of conductive networks within the biopolymer matrix, as well as an increase in dielectric relaxation phenomena due to interfacial and dipolar polarization.

Microwave absorption analysis clearly demonstrates that sugarcane bagasse-based composites with multi-walled carbon nanotubes (MWCNTs) exhibit excellent electromagnetic attenuation

performance in the X-band. Among these composites, Sample S4 stands out due to its superior reflection loss, wide bandwidth, and nearly complete absorption of incident waves

5.5 Comparative Evaluation of Electromagnetic Wave Absorption in Biowaste-Derived Composite Materials

Table 5.8 provides a detailed comparative analysis of the dielectric properties and microwave absorption performance of various biowaste-derived composite materials, including the proposed sugarcane bagasse-multiwalled carbon nanotubes (SG-MWCNTs) composite absorber. This evaluation highlights the effectiveness of various agricultural waste-based materials, combined with conductive additives like charcoal, coal, carbon nanotubes (CNTs), or rubber tire dust, in reducing incident electromagnetic waves. The proposed SG-MWCNTs composite, created using 3 wt.% MWCNTs and featuring a thickness of 4 mm, exhibited a dielectric constant of 4.4, a tangent loss of 0.131, and reached a minimum reflection loss of -22.8 dB at 8.8 GHz. Additionally, it had a -10 dB absorption bandwidth of 2.2 GHz. These results show that over 99% of incident microwave energy is absorbed at this frequency, making it highly efficient in the X-band region.

Table 5.8 Comparison of proposed outcomes with significant existing outcomes

Agriculture residue	Additives	shape	Dimensions (W × L × T)	Dielectric constant	Tangent loss	Reflection loss (dB)	Frequency (GHz)	Ref.
Banana leaves	coal	pyramidal	15 cm × 15 cm × 2 cm	1.99	0.024	-50	18	[94]
Coconut coir	charcoal	rectangular	W × L = 2.260 cm × 1.0160 cm	5.12	0.10	-27	8–12	[176]
Banana Leaves	charcoal	Double Layer	6 cm × 6 cm × 0.802 cm	4.83	0.18	-32.6	8.341	[128]
Cornhusk	charcoal	Single layer	6cm×6cm×1.08cm	3.59	0.13	-50.2	19.2	[93]
Rice husk +Rice husk Ash+ CNTs	CNTs	Multi-layer	45 cm × 45 cm × 1 cm	7.08	2.07	-20	6	[120]
Rice husk	coal	3 × 3 pyramidal Array	5 cm × 5 cm × 2 cm Pyramid height = 13 cm	2.504	0.085	-75	15	[117]
Coconut coir Dust	-	Test sample (WR 68)	2.3 cm × 1.1 cm × 0.3 cm	3.32	0.75	-23.5	10	[106]
Rice husk ash	CNTs	Single layer	450mm× 450mm ×10 mm	-	-	-20.4	3.2	[177]
Rice husk	CNTs	Single layer	200 mm × 200 mm × 2 mm	-	-	-18.5	14.4	[124]

Sugarcane bagasse	Rubber tire dust	rectangular	15.7mm × 7.8 mm ± 5 mm	3.38	0.04	-13.2	12.4-18	[118]
Sugarcane bagasse	3 wt.% MWCNTs	Test sample (WR90)	22.860mm×10.160 mm×3mm	4.4	0.131	-22.8	8.9	Work done

The proposed SG-MWCNTs absorber excels due to a well-optimized balance of critical parameters: a moderate dielectric constant, adequate dielectric loss, a wide absorption bandwidth, and particularly high absorption at X-band frequencies. These characteristics are essential for practical applications such as testing antennas, shielding electronic devices from electromagnetic interference (EMI), stealth and defence systems, and anechoic chamber linings. The rectangular sample design compatible with the WR90 waveguide measures 22.860 mm × 10.160 mm × 4 mm, making it suitable for testing and aligning with real-world system integration. Overall, this comparative assessment highlights the potential of sugarcane bagasse reinforced with multi-walled carbon nanotubes (MWCNTs) as a cost-effective, environmentally friendly, and high-performing bio-composite for microwave absorption applications. It exhibits competitive electromagnetic properties and sustainable benefits by utilizing agricultural waste, establishing itself as a practical alternative to traditional chemical or synthetic absorbers within the X-band frequency range.

5.6 Comparative analysis of SG-MWCNTs and DBL-MWCNTs composites at 4 mm thickness

Table 5.9 presents the comparison of dielectric properties for SG-MWCNT and DBL-MWCNT composites containing 3 wt.% MWCNTs at a 4 mm thickness. It is evident that the DBL-MWCNT composite exhibits higher values of real permittivity ($\epsilon' = 6.4$), imaginary permittivity ($\epsilon'' = 0.96$), loss tangent ($\tan \delta = 0.15$), and electrical conductivity ($\sigma = 0.49$ S/m) compared to the SG-MWCNT composite ($\epsilon' = 4.44$, $\epsilon'' = 0.59$, $\tan \delta = 0.13$, $\sigma = 0.26$ S/m). These enhanced dielectric parameters indicate stronger interfacial polarization and better energy dissipation capability in the DBL-MWCNT composite.

Similarly, Table 5.10 compares the microwave absorption performance of both composites in the X-band frequency range. The SG-MWCNT (3 wt.%) sample achieved a minimum reflection loss (RL) of -22.8 dB with an effective bandwidth of 2.2 GHz, whereas the DBL-MWCNT (3 wt.%) composite showed a significantly higher RL of -34.8 dB and a wider bandwidth of 3.4 GHz.

Table 5.9 Comparison of dielectric properties of SG-MWCNT with DBL-MWCNTs at a thickness of 4mm

Parameters	SG+(3wt.%MWCNT)	DBL+(3wt%MWCNT)
ϵ'	4.44	6.4
ϵ''	0.59	0.96
$\tan \delta$	0.13	0.15
σ (S/m)	0.26	0.49

Table 5.10 Comparison of Microwave absorption of SG-MWCNT with DBL-MWCNTs at a thickness of 4mm

Samples	Frequency (GHz)	Bandwidth below -10dB (GHz)	Bandwidth below -10dB (GHz)
SG+(3wt.%MWCNT)	8.2 to 12.4	-22.8	2.2
DBL+(3wt%MWCNT)	8.2 to 12.4	-34.8	3.4

These results clearly demonstrate that DBL-MWCNTs composites possess superior microwave absorption performance compared to SG-MWCNTs samples. The improved absorption behaviour of the DBL-MWCNTs composite can be attributed to its higher intrinsic carbon content and better dispersion of MWCNTs within the DBL matrix. The increased carbon content enhances electrical conductivity and dielectric polarization, leading to improved impedance matching and higher microwave attenuation.

Hence, it can be concluded from the result that DBL-MWCNTs composites exhibit superior dielectric and microwave absorption properties as compared to SG-MWCNTs composites, making them more promising candidates for advanced microwave absorber applications and further study.

5.7 Summary and Contribution of the Chapter

This chapter presents an in-depth examination of the advancement and execution evaluation of sugarcane bagasse (SG)-based bio-composites with multi-walled carbon nanotubes (MWCNTs) as effective microwave absorbers for X-band applications. Four composite samples, S1 (1 wt.% MWCNTs, 3 mm), S2 (1 wt.% MWCNTs, 4 mm), S3 (3 wt.% MWCNTs, 3 mm), and S4 (3 wt.% MWCNTs, 4 mm), were efficiently created to consider the impact of both filler concentration and thickness on dielectric and electromagnetic properties. Dielectric parameters such as dielectric constant, loss factor, tangent loss, and electrical conductivity were experimentally determined, followed by a measurable assessment through percentage error investigation and standard deviation. The information revealed an increasing trend in dielectric and conductive performance with higher MWCNT loading and more prominent thickness, suggesting progressive interfacial polarization and conductive network arrangement inside the

1 composite structure. Microwave absorption behaviour was calculated utilizing reflection loss (RL) and absorption percentage equations under PEC-backed conditions, successfully blocking transmission and enabling exact RL computation. The results demonstrated that both MWCNT content and sample thickness essentially influence absorption effectiveness. Sample S4 (3 wt.% MWCNTs, 4 mm) appeared to have the most excellent absorption performance, with the least RL of 22.8 dB at 8.8 GHz and an absorption bandwidth of 2.2 GHz (for RL < 10 dB), showing over 99.4% wave attenuation. Other samples moreover met viable criteria, with S3 and S2 achieving RL values of 12.9 dB and 12.3 dB, respectively, whereas S1 still achieved 10.6 dB. A comparative consider with existing biowaste-based microwave absorbers highlighted the superior execution of the SG-MWCNTs composite, not as it were in terms of reflection loss but too in material sustainability, low cost, and manufacture effortlessness. With its favorable dielectric constant (4.4), moderate loss tangent (0.131), and strong absorption capability, the developed SG-MWCNT composite demonstrates to be a reasonable, eco-friendly elective for utilize in electromagnetic interference (EMI) shielding, stealth advances, radio wire testing setups, and anechoic chambers. In Summary, this chapter contributes to the advancement of green microwave absorber technology by illustrating that the synergistic impact of increasing MWCNT content and material thickness in sugarcane bagasse composites leads to improved dielectric performance and superior microwave absorption, meeting the useful requirements of advanced X-band applications.

PUBLISHED WORK RELATED TO THIS CHAPTER:

- 25
- 119
1. A. Tripathi and K. S. Sandha, "Impact of thickness and wt% on the dielectric properties of sugarcane bagasse and MWCNT composite material as microwave absorber," *Waste and Biomass Valorization*, vol. 14, no. 6, pp. 2009–2024, 2023. (SCI indexed- Impact Factor – 2.8). <https://doi.org/10.1007/s12649-022-01977>

CHAPTER 6

ANALYZING THE IMPACT OF THERMAL VARIATIONS ON AGRICULTURAL WASTE-BASED MICROWAVE ABSORBER

This chapter experimentally examines the effect of temperature on the microwave absorption performance of agricultural waste-based materials. Specifically, the study examines dried banana leaves (DB) and a composite material formed by combining DB with multi-walled carbon nanotubes (MWCNTs). For this purpose, two types of samples were fabricated in dimensions compatible with the WG13 waveguide, one pure dried banana leaves and the other DB integrated with MWCNTs to potentially boost absorption performance. The experimental evaluation was carried out within the C-band frequency spectrum (3.7–7.4 GHz), employing a one-port vector network analyzer (VNA) together with the WG13 waveguide to accurately assess the electromagnetic response. To examine how well the materials maintain their functionality under varying thermal conditions, their absorption properties were tested at different temperature ranges

The main objective of this proposed study was to examine the temperature-dependent behaviour of dried banana leaves, an economical and renewable material with strong potential as a microwave absorber. Additionally, the influence of MWCNTs on improving the composite's electromagnetic attenuation performance was thoroughly examined. The findings contribute valuable knowledge toward the design of efficient, environmentally sustainable materials for future microwave absorption technologies.

6.1. INTRODUCTION

In advanced applications such as military tanks, submarines, and fighter jets, microwave absorber materials must reliably function under extreme and varying temperature conditions. These systems demand materials that maintain consistent absorption efficiency despite environmental fluctuations. At the same time, there is a growing need for solutions that are sustainable and cost-effective. Traditional synthetic absorbers, though effective, are often expensive and non-biodegradable. Agricultural waste-based materials, including dried banana leaves and sugarcane bagasse, provide a renewable and low-cost alternative. When combined with conductive additives like multi-walled carbon nanotubes (MWCNTs), these biocomposites exhibit improved dielectric properties and stable microwave absorption across a range of temperatures. In this study, composites developed from agricultural residues demonstrated that the dried banana leaves (DB)-MWCNT combination exhibited the best

microwave absorption performance among all samples. This particular composite was identified as a highly suitable candidate for further investigation due to its efficiency and eco-friendly nature. Building on these results, the current chapter focuses on exploring how temperature influences the microwave absorption properties of dried banana leaves and their MWCNT-based composite. This research is motivated by existing literature discussed in Chapter 2, which highlights that several researchers have explored the temperature dependence of microwave absorption in different materials. Most studies have focused on chemically synthesized or polymer-based absorbers, which, while effective, often emit toxic gases at high temperatures [48]. These emissions raise significant environmental and health concerns, particularly in applications that require thermal resilience. Consequently, there is an increasing demand for sustainable, non-toxic alternatives. Biowaste materials have emerged as a promising solution due to their availability, biodegradability, cost-effectiveness, and minimal environmental impact. Previous chapter experimental results have confirmed that even at room temperature, composites made from biowaste like dried banana leaves with MWCNT show significant microwave absorption capability. This makes them a convincing alternative to traditional chemical-based absorbers.

In this chapter, two types of samples were prepared based on WG13 waveguide compatibility. One sample was composed of pure DB, while the other was a composite of dried banana leaves with multi-walled carbon nanotubes (DB-CNTs). The investigation was conducted in the C-band (3.7 to 7.4) GHz frequency range. A one-port VNA was used alongside a WG13 waveguide to measure the electromagnetic characteristics accurately. To assess the thermal stability and practical usability of these materials in real-world applications, their microwave absorption behaviour was systematically studied over a temperature range of 20°C to 120°C.

6.2 MATERIALS AND METHODS

The preparation of the dried banana leaves (DB) and DB-CNTs (dried banana leaves with multi-walled carbon nanotube) composite samples involved a systematic process to ensure uniformity. After the samples were successfully prepared their carbon composition was analyzed to determine the elemental content and distribution. The microstructural characteristics of the sample surfaces were examined using a scanning electron microscope (SEM), which provided detailed imaging of their morphology and surface features. Furthermore, the high-temperature electromagnetic and microwave absorption characteristics of the samples were evaluated using a Rohde & Schwarz ZVH8 vector network analyzer

(VNA). VNA measurements were performed to evaluate the reflection and absorption properties of the samples across the C-band, confirming their potential as effective microwave absorbers at elevated temperatures..

6.2.1 SAMPLE FABRICATION METHOD

In this proposed study, banana leaves and polyester resin were used along with CNTs with 97% purity, surface area ranging from 90 to 220 m^2/g , 10 μm length, and 5 to 20 nm diameter to develop a microwave absorber material. The fabrication of the DB & DB-CNTs composite based on microwave absorber begins with taking green banana leaves, which are shown in Figure 6.1. In the first step, the leaves need to be cleaned thoroughly by washing them under running water multiple times. In next step, the biomass needs to be sun-dried for 3-4 weeks. After this, a home base grinder is used to grind the banana leaves. In next step, crude powder is sieved for finer powders. The banana powders can be characterized by non-uniform distribution of particles, which range from 140 μm to 520 μm . The size of the particles has major impact on material properties such as microwave absorbing capacity. When the particles are reduces to the micron range. The material displays higher degree of porosity, greater surface area, increased light scattering on the surface, and higher surface atom concentration [5]. When the dimension of an object decreases, its specific surface area increases. Once the powder of banana leaves integrated with CNTs is obtained, the following step is to develop the microwave absorber composite material. First mix the powder of banana leaves with MWCNTs and subsequently add it as a loading filler. Thereafter, MEKP and cobalt are added to the mixture of PRand stirred until a homogeneous mixture is achieved. The material is sonicated in the ultrasonic processor for 35 minutes to ensure optimal dispersion of the material. Polyurethane and phenol-formaldehyde were used previously by multitude of studies towards the development of microwave absorbers [179]. However, these types of resin are not eco-friendly and can be hazardous to human health[10]. Thus, in this proposed study a binder of PR was used and the hardener agent of MEKP, along with cobalt as an accelerator, was used for making samples of microwave absorbers. Also, the use of polyester resin and methyl ethyl ketone peroxide enhances erosion resistance and helps in binding materials, thus preventing air gaps between particles[5]. This weight ratio must sustain 80:20 of polyester resin and methyl ethyl ketone peroxide for the production of a microwave absorber sample. Then, composites of DB-CNTs are positioned in a rectangular mold of 40.386mm $\times$ 20.193mm $\times$ 3mm to set at room temperature for 1 day. Thus, after one day created the DB and CNTs composite samples. After

that, proceed to measure all the samples with a VNA to determine their microwave absorption characteristics for the C-band frequency.

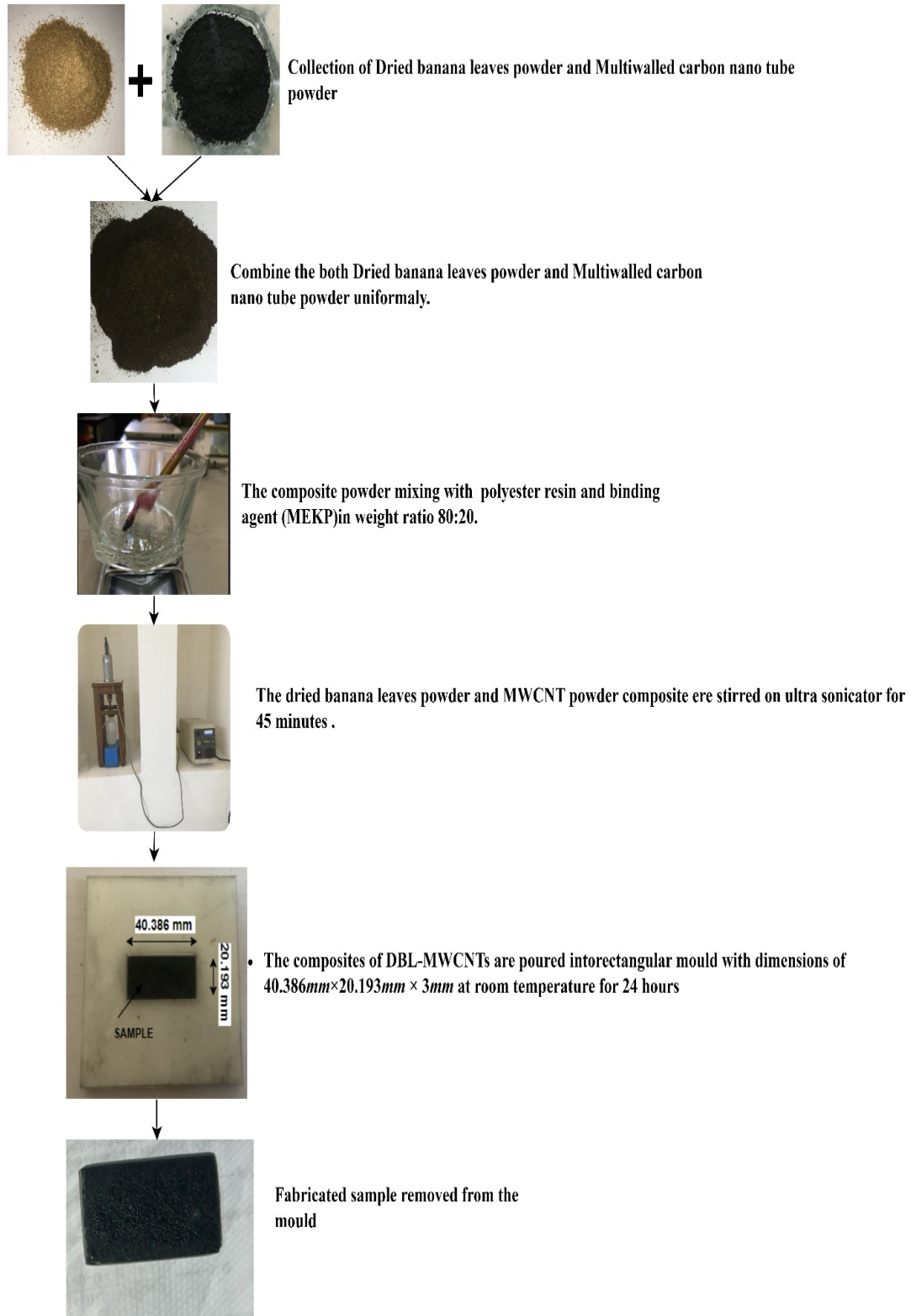


Figure 6.1 Steps of fabrication DB and DB-CNTs composite-based microwave absorber

6.3 CHARACTERIZATIONS

6.3.1 Scanning Electron Microscopy (SEM)

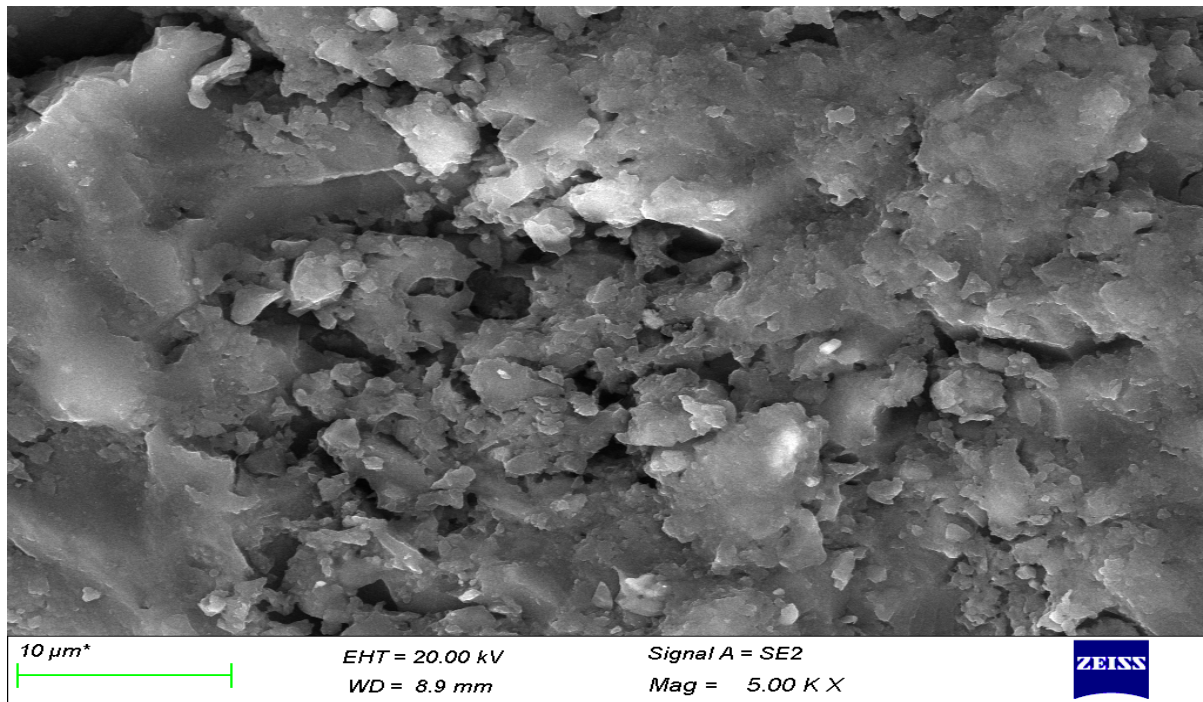


Figure 6.2 SEM image of DB-CNTs with magnification of $10\mu\text{m}$

Figure 6.2 shows an SEM image of the DB-CNTs composite material taken at $10\mu\text{m}$ magnification, revealing the details about its microstructure. At lower magnification, the surface of the composite reveals an undulating, sheet-like structure that appears dense, tough, and slightly fractured, indicating a strong and stable matrix likely resulting from the effective incorporation of CNTs into the dried banana leaves (DB) matrix. The image also shows numerous pores throughout the material, which are crucial for enhancing microwave absorption. Porous structures facilitate the scattering, absorption, and dissipation of EM waves. Thus, the SEM image not only highlights the surface morphology and porosity of the DB-CNT composite but also demonstrates structural features that contribute to its effective electromagnetic wave absorption.

6.3.2 Elemental Analysis of DB and DB-CNT Composite

Table 6.1 presents the elemental analysis of dried banana leaves (DB) using CHNS analysis. The carbon content in DB is 42.34%, with additional elements like hydrogen and nitrogen.

3

Table 6.1. CHNS Elemental Analysis of Dried Banana Leaves

Elements	Carbon (C)	Hydrogen (H)	Nitrogen (N)	Sulphur (S)
DB (Dried banana leaves)	42.34%	5.47%	0.56%	-

Table 6.2. ELEMENT Analysis of DB-CNT composite (EDS Analysis)

Points	Carbon (C)	Oxygen(O)	Chlorine (Cl)
B.1	77.53%	20.07%	1.37%
B.2	78.199%	19.33%	1.34%
B.3	83.46%	14.01%	1.12%
B.4	87.17%	10.54%	1.225

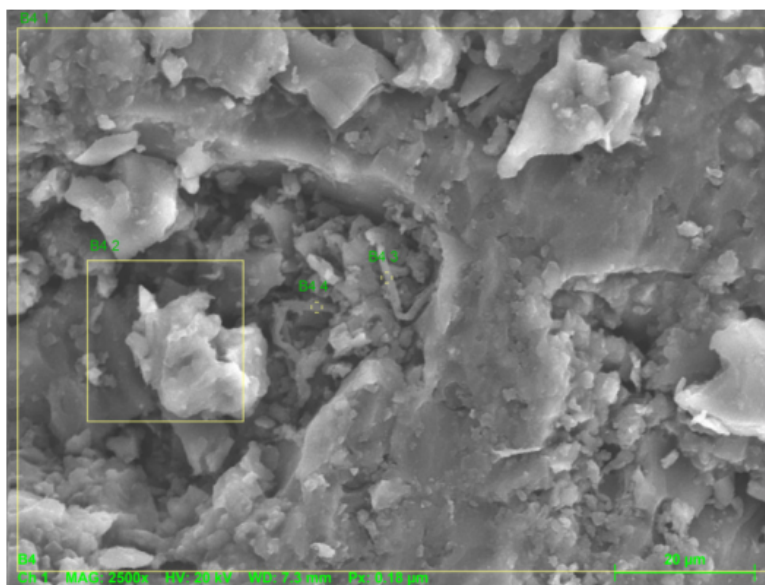


Figure 6.3 Scanning Electron Microscope analysis with an Energy-Dispersive X-ray Spectroscopy detector analysis of elemental composition of DB-CNTs composite.

After incorporating 5 wt% of CNTs into DB, the carbon content increased significantly, as shown in Table 6.2. Scanning Electron Microscope (SEM) analysis with an Energy-Dispersive

6

X-ray Spectroscopy (EDS) detector was conducted to determine the elemental composition of the dried banana leaves (DB) combined with multi-walled carbon nanotubes (CNTs). The EDS analysis was performed at four specific points (B.1, B.2, B.3, and B.4) on the composite sample and the results confirm a notable rise in carbon content are shown in Figure 6.3 The SEM image taken at 2500x magnification (scale bar: 20 μm) shows the surface morphology of the DB-CNT composite. The image reveals the presence of DB powder particles and CNT fibers with the EDS analysis performed at four selected points. Point B.1 shows Carbon content is 77.53%, with 20.07% oxygen. Point B.2 shows Carbon content is 78.199%, with 19.33% oxygen. Point B.3 is located on the CNT fibers, showing a higher carbon content of 83.46% and a lower oxygen content (14.01%). Point B.4 is another CNT fiber point, with 87.17% carbon and 10.54% oxygen. These results clearly indicate a significant increase in carbon content compared to pure dried banana leaves (42.34% carbon). The addition of CNTs enhances the carbon composition and strengthens its potential as an efficient microwave-absorbing material with enhanced thermal stability.

6.4 EXPERIMENTAL SET UP

The microwave absorption characteristics of the prepared samples were tested within the C-band frequency range using a one-port VNA, ROHDE & SCHWARZ ZVH8 for data collection. A WG13 rectangular waveguide was employed in the experiment, and the samples were precisely cut to match its dimensions (40.386 mm $\times$ 20.193 mm $\times$ 3 mm). To prevent microwave transmission through the sample, a metal back plate was placed behind it, ensuring that the measurements focused solely on the reflected microwaves. Figure 6. 4(a) illustrates the schematic representation of the experimental setup, where a single port of the VNA is connected to a coaxial cable. The cable is linked to the waveguide where the material under test (MUT) is positioned. A metal back plate is placed behind the sample to block microwave transmission, allowing for accurate reflection measurements [9]. Figure 6.4 (b) depicts the actual experimental setup where the VNA is connected to the waveguide via a coaxial cable. The sample is placed inside the waveguide, followed by the metal back plate, and the RL(S_{11} parameter) is displayed on the VNA screen. The S_{11} parameter also known as reflection loss which represents the amount of microwave energy reflected by the material thereby indicating its absorption efficiency [180]. The microwave absorption performance of the samples can be evaluated by analyzing reflection loss across the C-band frequencies.

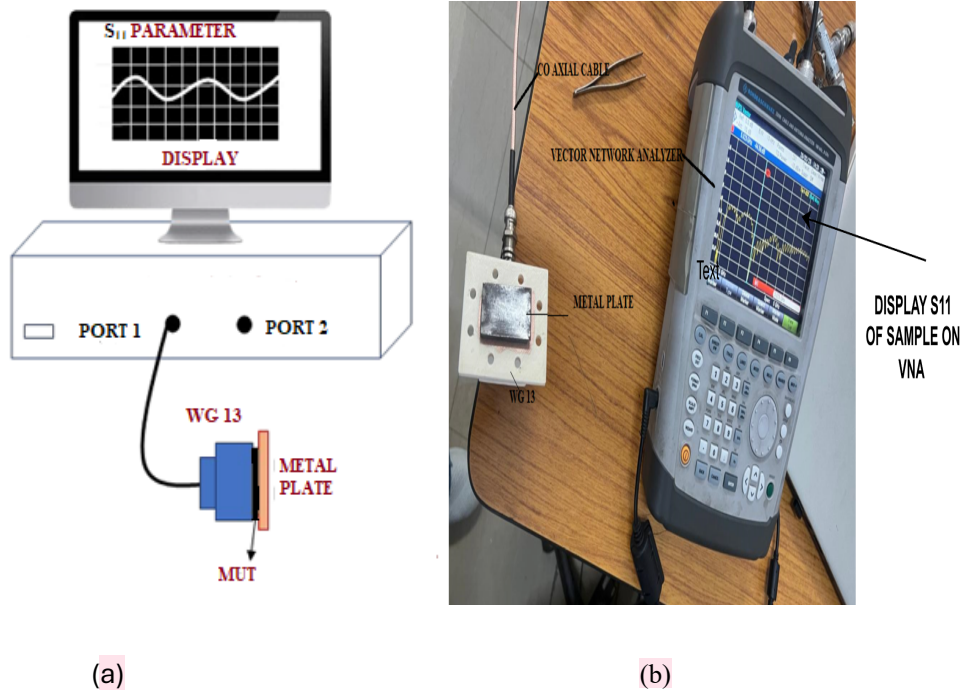


Figure 6.4 Experimental setup (a) Schematic representation of the experimental setup. (b) Actual experimental setup used for measuring the S_{11} scattering parameter with a one-port VNA.

6.5 Impact of Temperature on Microwave Absorption Performance

6.5.1 Reflection loss

The microwave absorption characteristics of the synthesized samples, DB and DB-CNTs, were evaluated within the C-band frequency range using a one-port VNA at temperatures ranging from 20°C to 120°C. The experiment utilized a WG 13 waveguide, and the dimensions of the samples (40.386 mm x 20.193 mm x 3mm) were compatible with those of the WG 13 waveguide, as illustrated in Figure 6.5. As shown in Figure 6.5, the samples were heated on a heating plate to the desired temperature, which was measured precisely using an infrared thermometer. After heating, each sample was placed between the WG 13 waveguide and a metal back plate, which prevents microwave transmission. A coaxial cable connected the waveguide to Port A of a VNA to measure the S_{11} parameter, representing the reflected microwave signal. The S_{11} data, also referred to as reflection loss, indicate the material's microwave absorption efficiency[10]. This measurement setup was used to evaluate and compare the EM wave absorption performance of both dried banana leaves(DB) and DB-CNTs composite samples. The reflection loss (RL) is defined according to transmission line theory, as expressed in Equation (3.13).

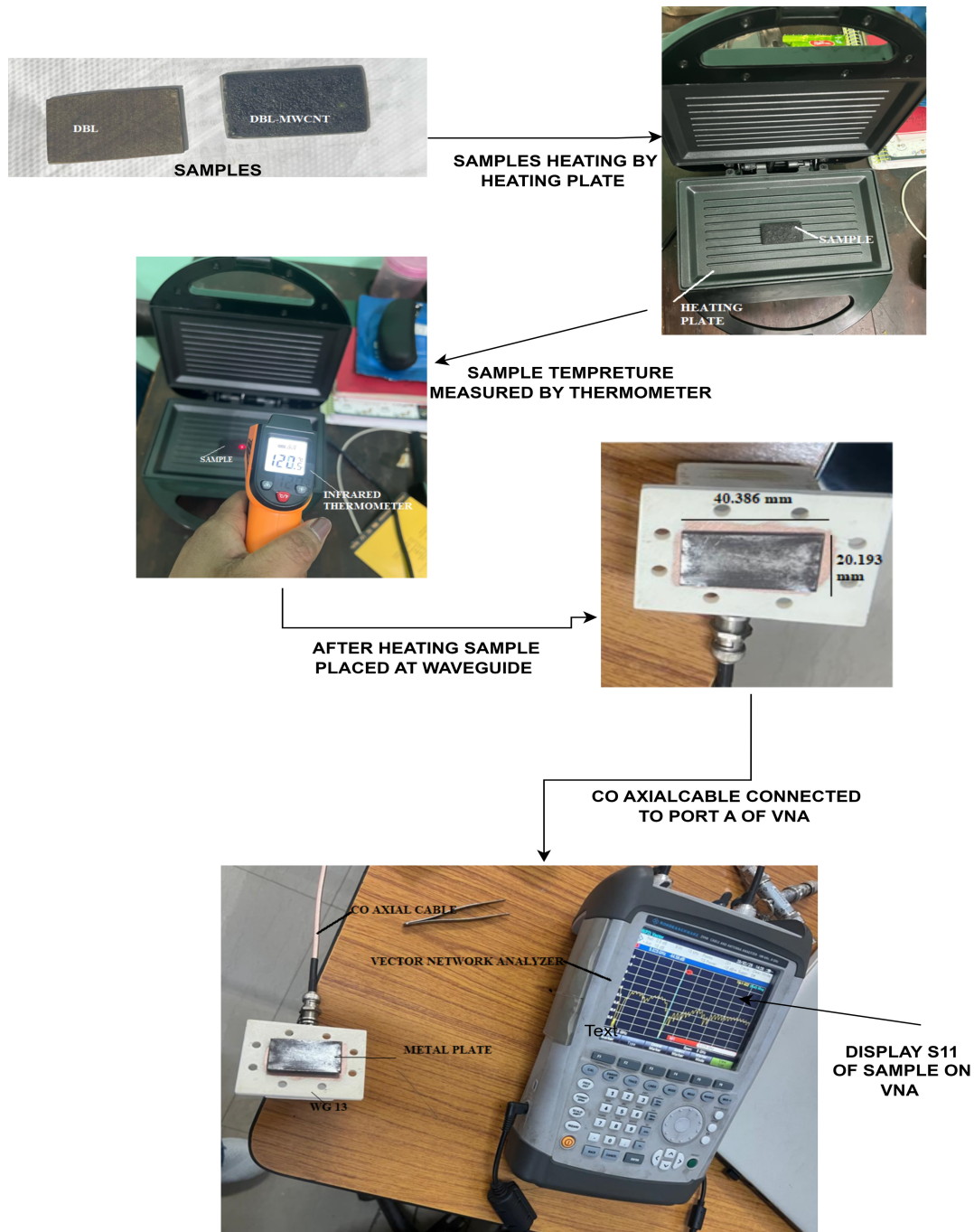
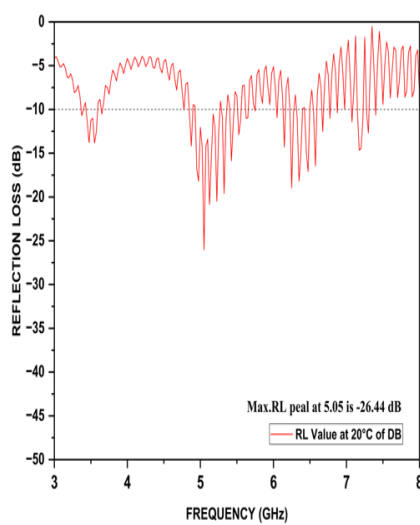


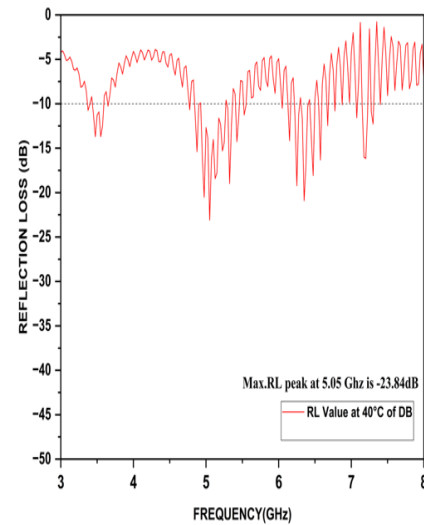
Figure 6.5 Schematic representation of reflection loss measurement of DB and DB-CNT at different temperatures.

According to transmission line theory as defined in equation (3.13), two major factors play an important role in RL: (1) the impedance matching (the match between input impedance Z_{in} and free space impedance Z_0) and (2) the dielectric and magnetic properties of the absorber material[140]. In this proposed study, dried banana leaves, a biowaste material lacking inherent magnetic properties, were used to fabricate the microwave absorber. For effective absorption, a microwave absorber must exhibit a minimum RL below -10 dB, corresponding to more than

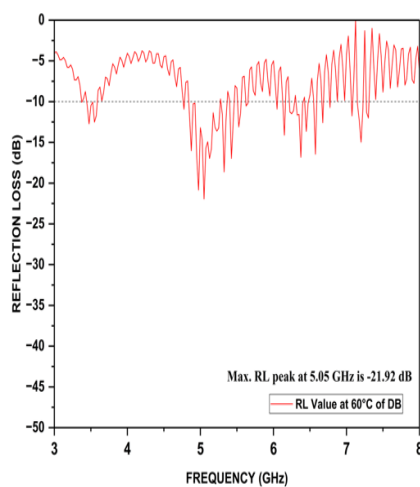
90% absorption of incident microwave energy. An ideal absorber merges various loss mechanisms with good attenuation and proper impedance matching [140]. The microwave absorption characteristics of the DB were analyzed within the C-band. Figure 6.6 illustrates the variation of reflection loss (RL) with increasing temperature. The temperature-dependent microwave absorption performance of DB was investigated across the temperature range of 20°C to 120°C at a fixed sample thickness of 3 mm within the C-band frequency range. The RL curves at each temperature reveal a consistent peak absorption centered around 5.05 GHz. However, the intensity of absorption exhibits noticeable decline as the temperature increases.



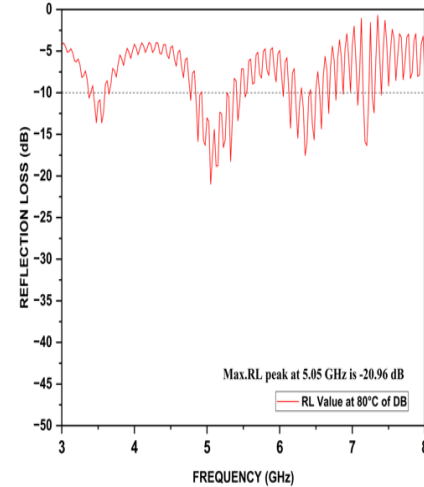
(a)



(b)



(c)



(d)

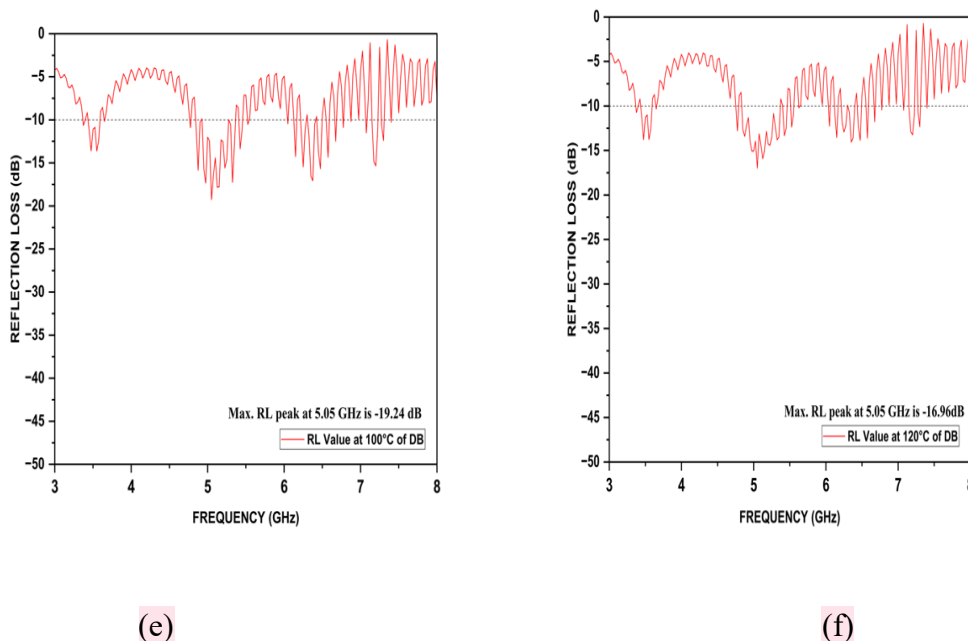
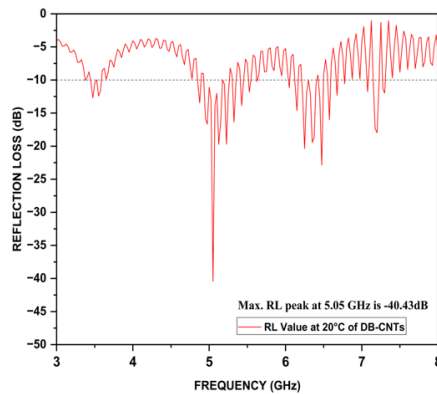


Figure 6.6 Temperature-dependent RL performance of DB at (3 mm) in the C-band.. Each subplot (a)–(f) represents the RL value at a specific temperature (20°C to 120°C)

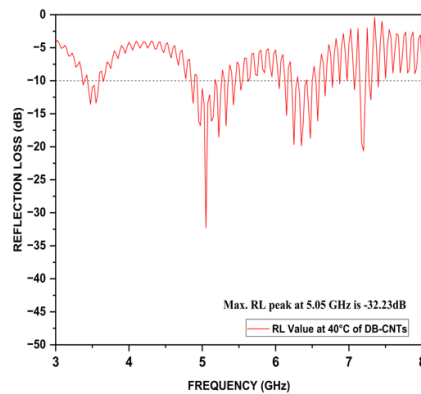
At room temperature (20°C) the DB sample demonstrates the highest microwave absorption capability with a maximum RL value of -26.44 dB. As the temperature increases to 40°C and 60°C the peak RL reduces to -23.84 dB and -21.92 dB respectively indicating a progressive degradation in absorption performance. Further heating to 80°C, 100°C, and 120°C results in RL values of -20.96 dB, -19.24 dB, and -16.96 dB, respectively. This decreasing trend can be attributed to temperature-induced changes in the physicochemical and dielectric properties of the material. At elevated temperatures the internal structure of the banana leaves undergoes partial degradation including the breakdown of hemicellulose and lignin components which are critical to maintaining effective dielectric polarization. Additionally, the evaporation of inherent moisture content and the collapse of natural pores and interfaces likely reduce the capacity for interfacial and dipolar polarization both of which are essential mechanisms in microwave absorption. These structural and dielectric deteriorations ultimately weaken the materials ability to convert electromagnetic energy into thermal energy resulting in reduced reflection loss values [181]. Thus, the results suggest that the microwave absorption efficiency of DB is optimal at lower temperatures, where the material retains its natural dielectric characteristics and internal morphology.

Figure 6.7 illustrates the temperature-dependent reflection loss (RL) characteristics of the dried banana leaves with Multi-Walled Carbon Nanotubes (DB-CNTs) composite measured within

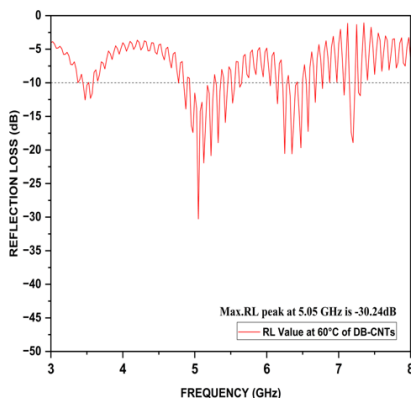
the C-band (3.7–7.4 GHz) frequency range at temperatures ranging from 20 °C to 120 °C. All measurements were conducted at a fixed material thickness of 3 mm. The RL spectra reveal that the composite consistently exhibits strong absorption around 5.05 GHz across the entire temperature range. However, the magnitude of absorption progressively decreases with increasing temperature. At 20 °C the composite demonstrates its highest microwave attenuation performance achieving a maximum RL of -40.43 dB. As the temperature rises to 40 °C and 60 °C the RL values slightly reduce to -32.23 dB and -30.24 dB, respectively, indicating sustained but gradually diminishing absorption. Further increases in temperature to 80 °C, 100 °C, and 120 °C result in RL values of -29.14 dB, -28.5 dB, and -24.18 dB, respectively, confirming a clear trend of reduced microwave absorption efficiency as thermal conditions intensify.



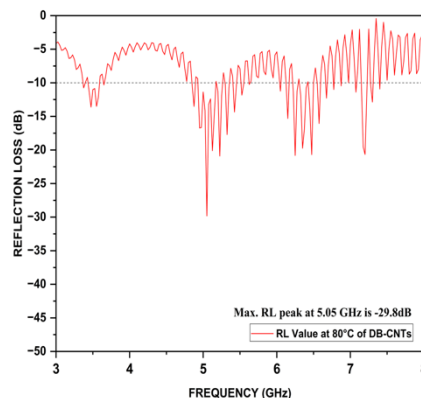
(a)



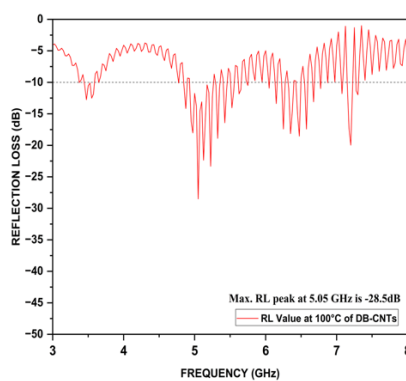
(b)



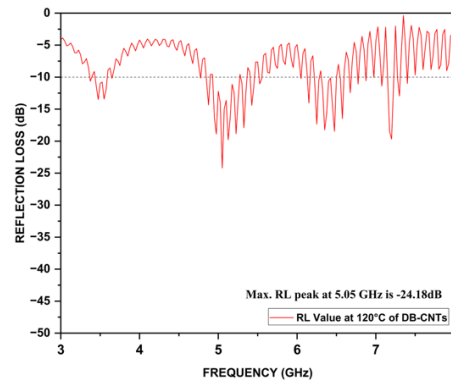
(c)



(d)



(e)



(f)

Figure 6.7 Temperature-dependent RL performance of DB-CNTs composite (3 mm) in the C-band. Each subplot (a)–(f) represents the RL value at a specific temperature (20°C to 120°C).

This reduction in absorption capability at elevated temperatures can be attributed to several key factors. Firstly, thermal agitation at higher temperatures disrupts the structural and interfacial integrity of the composite material particularly at the interface between the dried banana leaves matrix and the embedded multi-walled carbon nanotubes (MWCNTs). This disruption weakens the multiple dielectric relaxation processes and reduces the interfacial polarization effects that are essential for effective electromagnetic wave attenuation. Secondly, the increase in temperature may cause partial thermal degradation or softening of the DBL matrix resulting in reduced compatibility and contact between the DBL and the conductive CNT network thereby diminishing the composite's ability to dissipate electromagnetic energy. Lastly, excessive temperature may also reduce the dielectric contrast between the filler and matrix, limiting the composite's ability to trap and absorb microwave energy through multiple reflections and scattering mechanisms. These observations suggest that while the DB-CNTs composite retains good microwave absorption properties even at higher temperatures its optimal performance is achieved at lower thermal conditions where structural integrity and interfacial interactions are better preserved.

The proposed study of temperature-dependent microwave absorption characteristics reveals distinct behaviours for both pure DB and DB-CNTs composite materials. For the DB sample, the RL progressively decreased from -26.44 dB at 20°C to -16.96 dB at 120°C , indicating a steady decline in absorption performance with rising temperature. This degradation is attributed to the breakdown of natural components such as hemicellulose and lignin, as well as

the collapse of porous structures and loss of dipolar polarization, all of which reduce the material's ability to absorb electromagnetic waves effectively.

In contrast, the DB-CNTs composite showed superior absorption capabilities across the entire temperature range with the highest RL of -40.43 dB at 20°C and still maintaining a strong RL of -24.44 dB at 120°C . The presence of MWCNTs significantly enhances dielectric loss, interfacial polarization, and electrical conductivity making the composite stronger to temperature-induced degradation. However, a decreasing trend with temperature was also observed in the composite though the extent of decline was less severe compared to pure DB. Overall, the experimental results confirm that the DB-CNTs composite not only outperforms the pure DB in terms of reflection loss values but also maintains better thermal stability. Therefore, incorporating carbon nanotubes into agricultural biowaste matrices like dried banana leaves is an effective strategy to develop high-performance, thermally stable, and eco-friendly microwave absorber materials for C-band applications such as satellite communications, radar systems, defence, and wireless networks.

6.5.2 Absorption Power

When electromagnetic waves hit the sample that's supported by a metal plate, they either get absorbed or reflected but they don't pass through. The percentage of power that's absorbed calculated by equation (3.18). This equation quantifies the microwave absorption efficiency of the material by calculating the proportion of incident power absorbed by the sample. The microwave absorption efficiency of the DB and DB-CNTs composites was further investigated by calculating the absorption power percentage at varying temperatures. As RL is a direct measure of how much incident microwave energy is reflected by a material a more negative RL value indicates stronger microwave attenuation. Once the RL values across different temperatures were obtained the corresponding absorption percentage was calculated. Table 6.3 presents the absorption power percentages of both DB and DB-CNTs samples across a temperature range from 20°C to 120°C at a fixed thickness of 3 mm . For the DB sample a high initial absorption of 99.7% was recorded at 20°C . However, as the temperature increased a gradual reduction in absorption efficiency was observed with values decreasing to 99.5% at 40°C , 99.4% at 60°C , 99.2% at 80°C , 98.8% at 100°C , and finally 97.8% at 120°C . This trend can be attributed to the thermal degradation of organic constituents in the dried banana leaves, such as cellulose, hemicellulose, and lignin, which lead to a decline in dipolar polarization and interfacial interactions both of which are critical for effective dielectric loss mechanisms.

Despite this decline, the DB material still maintains RL values below -10 dB across all temperature points, confirming that it continues to function effectively as a microwave absorber. According to standard electromagnetic absorption criteria, an RL below -10 dB indicates that more than 90% of incident energy is being absorbed thereby validating the pure dried banana leaves (DB) usability even under elevated thermal conditions.

Table 6.3 Absorption power percentage of DBL and DBL-MWCNTs materials at different temperatures

Material	Thickness (mm)	Temperature °C	Absorption percentage (%)
Dried banana leaves (DBL)	3	20	99.7
		40	99.5
		60	99.4
		80	99.2
		100	98.8
		120	97.8
Dried banana leaves with multiwalled carbon nano tubes (DBL- MWCNTs)	3	20	99.9
		40	99.9
		60	99.9
		80	99.8
		100	99.8
		120	99.6

In contrast, the DB-CNTs composite sample exhibited remarkably stable absorption behaviour throughout the same temperature range. At 20°C , 40°C , and 60°C , the absorption power was measured consistently at 99.9%, with only a marginal decrease to 99.8% at 80°C and 100°C , and 99.6% at 120°C . This outstanding thermal stability can be credited to the synergistic effect between the banana leaves matrix and the embedded MWCNTs. The incorporation of MWCNTs introduces enhanced electrical conductivity, interfacial polarization, and multiple scattering effects which significantly boost dielectric loss mechanisms. Additionally, the highly

conductive network formed by the MWCNTs ensures that the composite maintains effective impedance matching with free space even as the temperature increases thereby minimizing reflection and maximizing absorption. Unlike the pure DB sample which experiences a moderate decline in performance at higher temperatures, the DB-CNTs composite retains near-constant absorption levels showcasing its superior electromagnetic attenuation capabilities. From a comparative perspective, both materials exhibit high absorption efficiency above 97% across the entire temperature range. However, the DB-CNTs composite clearly outperforms the pure DB, particularly under high-temperature conditions where its stability and effectiveness remain nearly unchanged. This indicates that while DB alone is a promising eco-friendly and cost-effective microwave absorber, the integration of MWCNTs substantially improves its performance especially in thermally stressed environments. From the result, it's observed that both DB and DB-CNTs samples are viable candidates for use in high-temperature microwave absorption applications. The DB sample despite minor performance drops at elevated temperatures still meets the critical RL -10 dB requirement validating its potential. Meanwhile, the DB-CNTs composite demonstrates excellent thermal stability and near-perfect absorption making it exceptionally well-suited for demanding applications such as stealth technology, radar absorption, defence and thermal-resistant electromagnetic shielding, where consistent performance under varying thermal conditions is essential.

6.6 Comparative Analysis Microwave Absorption Performance of DB, DB-CNTs and Conventional Absorbers

The Table 4 compares the microwave absorption performance of various materials, including chemically synthesized composites and the natural DB and DB-CNTs composites. The chemically engineered materials, such as ZnO@CNTs , $\text{Fe}_3\text{O}_4\text{-CNTs/SiO}_2$, MWNT/SiO_2 , $\text{Al}_2\text{O}_3\text{-MoSi}_2/\text{C}$, and SiC -based composites generally operate in the X-band (8.2–12.4 GHz) with high-temperature stability up to 600–700°C. These materials exhibit strong absorption with minimum reflection loss (RL) values ranging from -17 dB to -37 dB , making them highly effective for microwave wave attenuation.

Table 6.4 Comparison of Microwave Absorption Performance of DB and DB-CNTs Composites with Chemically Synthesized Absorbers

Materials	frequency	Thickness (mm)	RL(dB)	T(°C)	References
ZnO@CNTs	(8.2–12.4 GHz)	2.5	-20.7 dB at 50°C	50°C - 400°C	[182]

Fe₃O₄-CNTs/SiO₂	(8.2–12.4 GHz)	3.2	-24.8 dB at 50°C	50°C–200°C	[183]
MWNT/SiO₂	(8.2–12.4 GHz)	2.5	-20 dB at 30°C	30°C – 600°C	[184]
Al₂O₃–MoSi₂/C	(8.2–12.4 GHz)	1.4	-17 dB at 20°C	20°C - 700°C	[185]
SiC_f/Al₂O₃–SiO₂	(8.2–12.4 GHz)	3	-37 dB at 200°C	200°C - 600°C	[186]
SiC_f/BN/AlPO₄/CNTs	(8.2–12.4 GHz)	3.1	-33 dB at 200°C	25°C - 600°C	[187]
DB	(3.7–7.4 GHz)	3	-16.96 dB at 120°C	20°C–120°C	This work
DB-CNTs	(3.7–7.4 GHz)	3	-24.8 dB at 120°C	20°C–120°C	This work

In contrast, DB and DB-CNTs composites operate in the C-band (3.7–7.4 GHz) and show moderate absorption. The DB-CNTs composite exhibits enhanced performance compared to DB alone, achieving a minimum RL of -24.8 dB at 120°C, while DB alone reaches only -16.96 dB. Although DB-based materials have lower absorption performance than advanced ceramic-based absorbers, their biodegradability, cost-effectiveness, and sustainability make them attractive alternatives for environmentally friendly microwave absorption applications. While high-temperature chemical materials remain superior in extreme environments, DB-CNT composites offer a promising balance of absorption efficiency, lightweight properties, and eco-friendliness, making them viable for EMI shielding and radar absorption in lower-frequency applications.

6.7 Summary and Contribution of the Chapter

This chapter provides a detailed experimental study on biowaste-derived materials' temperature-dependent microwave absorption properties, specifically dried banana leaves

(DB) and their composite with multi-walled carbon nanotubes (DB-CNTs). Two types of samples were manufactured by WG13 waveguide dimensions to ensure compatibility with the experimental setup. The investigation was done in the C-band frequency range (3.7–7.4 GHz) using a one-port vector network analyzer (VNA) setup, and the performance of both materials was analyzed across a temperature range of 20°C to 120°C. The experimental result showed that pure DB exhibits reasonable absorption properties at room temperature. Its performance reduces significantly as the temperature increases. This decline is primarily due to the loss of moisture, reduction in dipolar polarization, and thermal-induced structural changes, which disrupt the impedance matching required for optimal absorption. In contrast, the DB-CNTs composite showed an extraordinary improvement in absorption efficiency and thermal stability, achieving a minimum reflection loss of -40.43 dB at 20°C and maintaining strong absorption (-24.18 dB) even at 120°C. This performance is attributed to the synergistic contribution of CNTs, which enhance conduction losses, enable multiple scattering mechanisms, and sustain better impedance matching under thermal stress. This chapter confirms that the inclusion of MWCNTs improves the electromagnetic properties of DB-based absorbers and addresses the limitations related to thermal degradation. This proposed work highlights the potential of converting agricultural waste into high-performance, eco-friendly, and thermally robust microwave absorbing materials. The DB-CNT composite is a promising candidate for electromagnetic interference (EMI) shielding and radar absorption applications, especially in environments subjected to temperature fluctuations such as aerospace, defense, and communication systems. The chapter contributes significantly to the field of sustainable material development by demonstrating the viability of biowaste-based absorbers as practical alternatives to conventional chemical-based materials. Moreover, it lays the groundwork for future exploration into such composites' mechanical and long-term thermal performance, supporting their potential transition from laboratory research to real-world deployment.

PUBLISHED WORK RELATED TO THIS CHAPTER:

1. Anju Tripathi and Karmjit Singh Sandha, “Analyzing the Impact of thermal variations on agricultural waste-based Microwave Absorber.” *Waste and biomass valorization*. (Communicated) (IF- 2.8).(Springer)

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

A set of conclusions has been drawn using the experimental results obtained in the thesis. The following sections of this chapter contain the conclusion and future work scope.

7.1. CONCLUSION

The research work presented in this thesis focused on the development, modeling, and performance evaluation of bio-waste material based on SG, DBL AND TWSD and biowaste-composite microwave absorber materials based on dried banana leaves (DBL) and sugarcane bagasse (SG) reinforced with multi-walled carbon nanotubes (MWCNTs). The main objective was to explore sustainable, eco-friendly, and cost-effective alternatives to traditional chemical-based microwave absorbers while achieving enhanced absorption performance in the X-band frequency range.

In the initial phase of this work, an extensive review of microwave absorption mechanisms, such as dielectric loss, magnetic loss, interfacial polarization, multiple scattering, and impedance matching, was conducted. The limitations of conventional absorbers, including high cost, environmental hazards, and limited absorption bandwidth, were discussed in detail. This laid the foundation for understanding the advantages of using biowaste-based materials and biowaste material combined with nanostructured fillers like CNTs.

Further, the effects of several parameters on microwave absorption performance, including absorber thickness, CNT loading, frequency range, and temperature variations, were thoroughly investigated. The experimental studies demonstrated that the incorporation of MWCNTs into DBL and SG matrices significantly improved the reflection loss (RL) and absorption bandwidth compared to pure biowaste absorbers. The results revealed that optimized CNT loading and absorber thickness enhanced the electromagnetic wave attenuation, indicating stronger energy dissipation within the composite material.

The work also highlighted the impact of temperature on the performance of the composites, which is crucial for practical applications in thermally variable environments. It was observed that reflection loss and absorption bandwidth were affected by changes in operating temperature, which could influence the long-term reliability of the materials. The analysis

provided important insights into thermally aware design considerations for biocomposite MAMs.

In addition, this research conducted a comparative study between DBL-MWCNT and SG-MWCNT composites. Although both materials demonstrated promising absorption capabilities, DBL-MWCNT composites exhibited slightly superior performance in terms of maximum reflection loss and broader absorption bandwidth under similar thickness and CNT loading conditions. These findings suggest that different biowaste sources can be selectively employed depending on the desired frequency response and application requirements.

To support the experimental observations, analytical modeling of the reflection loss and absorption bandwidth was performed. The developed models accurately predicted the performance of the composites across varying thicknesses, CNT concentrations, and temperatures. This demonstrated the feasibility of designing biocomposite MAMs with tailored properties to meet specific application needs in wireless communication, radar stealth technology, and electromagnetic interference (EMI) shielding.

Overall, it is concluded that biowaste-based MAMs reinforced with CNTs are promising candidates for next-generation microwave absorber materials. They not only provide environmental benefits and cost-effectiveness but also deliver enhanced absorption performance suitable for X-band applications. The study confirms that careful optimization of material composition, filler loading, thickness, and thermal considerations is essential to achieving superior microwave absorption.

7.2. FUTURE SCOPE OF WORK

The work presented in this thesis highlights the significant potential of DBL-MWCNT and SG-MWCNT composites as environmentally friendly and efficient microwave absorbers. However, several areas remain open for further investigation and improvement. The following points provide a detailed roadmap for future research:

In the nanoscale and microscale design of MAMs, it is essential to further improve impedance matching by incorporating hybrid fillers, such as combining CNTs with magnetic nanoparticles, graphene, or other nanostructured materials. This can simultaneously enhance dielectric and magnetic loss, resulting in broader absorption bandwidth and higher reflection loss.

The temperature-dependent performance of biocomposite MAMs needs more extensive exploration. Long-term studies considering thermal aging, high-power microwave exposure, and environmental variations can provide insights into the reliability and durability of these materials in practical applications.

Further optimization of CNT dispersion techniques within biowaste matrices is crucial. Uniform dispersion can minimize aggregation, improve interfacial bonding, and maximize absorption efficiency. Advanced processing methods such as ultrasonication, chemical functionalization of CNTs, or hybrid solvent-assisted mixing can be explored.

At the circuit and device level, integration of these materials into practical absorber panels, shielding enclosures, and antenna systems should be considered. This will help bridge the gap between laboratory-scale experiments and industrial applications in telecommunications, defense, and consumer electronics.

Cost analysis and scalability of biocomposite MAM fabrication should be addressed in future work. Efficient production techniques that maintain material performance while reducing manufacturing complexity can promote wider adoption of these sustainable absorbers.

Development of simulation frameworks and predictive models that can accurately capture the effects of material composition, geometry, CNT loading, and temperature on microwave absorption will be beneficial for designers. Such models will allow for rapid optimization and reduce the need for extensive experimental trials.

Lastly, exploring new biowaste sources beyond banana leaves and sugarcane bagasse, such as rice husk, coconut coir, or wheat straw, can further expand the range of sustainable materials suitable for MAM applications. Combining these with CNTs or other nanofillers may lead to materials with enhanced performance, broader frequency response, and improved environmental sustainability.

In conclusion, the findings of this thesis establish a solid foundation for designing eco-friendly, cost-effective, and high-performance microwave absorber materials. Future research building upon this work can further enhance the performance, reliability, and practical applicability of biocomposite MAMs, paving the way for their adoption in advanced communication, defense, and electronics industries.

