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Review on Sustainable EMI Shielding Materials Developed from Biodegradable Waste: A Waste to Wealth Strategy

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Abstract

Environmental pollution, one of the critical challenges is associated with the rapid advancement of various technologies. The huge heap of waste generated as a part of technological revolution is a main source of environmental pollution and it is an obstacle which retards the progress of industries. Among the various types of environmental pollution, Electromagnetic interference (EMI) is also a major form which is caused by the telecommunication and electronic industry. EMI can damage the functioning of electronic devices and it is a severe threat to our health. Techniques to solve both these pollutions simultaneously are an emerging field of research. Recent studies introduce an efficient strategy to use recycled materials for developing EMI shielding materials. This approach can be equally beneficial for suppressing undesired EM radiations as well as the controlling of environmental pollution through recycling of waste materials. This review discusses the recent developments in the strategy of designing biodegradable EMI shielding materials by the use of environment friendly and biomass based sustainable materials.

Keywords: Waste management, EM pollution, EMI Shielding, Biodegradable, Recycling, Sustainable material

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1. Introduction

In this era of ultimate technological revolutions, energy and environment are the most discussed topics in the scientific society. Society urges the exploration of novel materials for energy and environment related applications to meet the expanding challenges. Along with the developments in various domains of society, different forms of pollutions are also arising. This include, air pollution due to the uncontrollable growth in automobile industry, water and soil pollution due to the improper methods of disposal of waste materials and the electromagnetic pollution. As a part of the introduction of highly advanced technologies such as 5G and Internet of things, the electromagnetic pollution has grown as a major challenge since it is a threat to the functioning of electronic devices as well as human health. People are getting exposed to these harmful electromagnetic (EM) radiations every day in varying intensity and duration. The EM field emerging from simple instruments such as television, mobile phones and microwave ovens can causes diseases as its strength and time of exposure. Since the antenna of the mobile phones is closely located to the brain it increases the possibility of brain cancer. The radiations from X-ray machine and other medical equipments are mainly considered as dangerous compared to the household devices since the radiations emitted from such instruments are ionizing radiations. Moreover, the exposure to EM radiations can even cause severe health issues such as cancer [1], [2]. Most commonly the EM pollution is caused by the interference of excessive EM radiations from various electronic devices, which is known as electromagnetic interference (EMI) [3], [4]. The need for electronic and telecommunication devices are increasing day by day. Moreover, recently many nations make use of electromagnetic radiations to jam the signals in the war fields and to damage the electronic devices in the ships, radars and also cause damages to the security systems. Best possible methods to overcome these huddles should be adapted. One such method is the fabrication of shielding materials which are capable of suppressing undesired electromagnetic radiations [5].

EMI shielding is the process of inhibiting EM radiations from penetrating into electronic gadgets through the phenomena such as reflection or absorption of radiation with the help of suitable shielding materials [3], [6]. The major mechanism of EMI shielding is different for different materials. The properties of materials which determine its primary mechanism of shielding are electrical conductivity, dielectric property and magnetic property. The material which possesses high electrical conductivity is capable of reflecting the incident EM wave because of the impedance mismatch between the material and the medium of propagation of EM wave. In dielectric and magnetic materials the suppression of incident radiation is by the mechanism of absorption. In this category of materials, electric or magnetic dipoles within the material will interact with the incident electromagnetic field and the incident energy will get dissipated as heat. Shielding by multiple internal reflections is observed in materials which have porous structure. In most of the materials all three mechanisms of shielding exists and the total shielding efficiency (SE_T) of the material will be the sum of the shielding efficiency due to reflection (SE_R), due to absorption (SE_A) and due to multiple reflections (SE_M) [7]–[10].

Among the various effective materials for EMI shielding, metals are the earliest and most studied one. High electrical conductivity of metals is the key feature for their preference as shielding materials [9], [11]. Lightweight, flexibility, low cost etc. are the essential requirements for a good shielding material. Metals fail to full fill these criteria since they have high molecular weight and most of the metals are costly. Also they have poor corrosion resistance which reduces their significance as a shielding material [12]–[15].

Various materials have emerged as EMI shielding materials, which have many superior qualities compared to metals. Carbon based materials are very common among EMI shielding materials since they exhibit outstanding conductivity and various forms of structures and morphologies. Carbon materials used for shielding include carbon black (CB), graphene, graphite, carbon nanotube (CNT), carbon aerogel, carbon foam etc. Mainly the three dimensional structures of carbon such as carbon aerogels, carbon sponges and carbon foams are attractive shielding materials as they are light in weight and have promising shielding efficiency. They are also found abundantly in nature [3], [14], [16]–[18].

Waste management is a huge huddle in modern world. Due to the modernization and industrialization heap of waste is generated day by day. Recycling is the best solution for the management of waste. Biomass waste materials are an excellent source of carbon and with proper techniques they can be used for the synthesis of multifunctional carbon-based materials. Tremendous amount of biomass waste materials are getting dumped without any recycling. Recently many researchers are designing innovative and sustainable method of developing multifunctional materials using these wastes. A major area where these studies can bring a visible transformation is the electronic industry. Various components in the electronic instruments and devices can be replaced by the recycled materials and this will lead to a huge revolution in the world. Since the biomass waste materials are environment friendly and will not cause any kind of pollution, there conversion into useful materials such as EMI shielding materials will be of great importance in future. Biomass materials can be effortlessly converted into carbon and hence will be a most appropriate candidate for fabrication of EMI shielding materials [19], [20]. In the modern world where sustainable development is a key factor, these kinds of researches are mandatory and it holds a good hope of recovering the wealth and prosperity of nature. In this manuscript, different strategies of developing biodegradable EMI shielding materials from waste materials are discussed on the basis of recent studies. Among the various techniques we have particularly focused on the methods which utilize natural and environment friendly waste materials.

2. Recycled Materials for EMI Shielding

Recently innovative ideas to fabricate EMI shielding materials are being explored which are environment-friendly as well as economical. Some outstanding studies include the specific strategy of using recycled bio waste materials for developing EMI shields [21], [22]. Mostly conducting, dielectric or magnetic materials are the fundamental part of an EMI shielding material. Recycled materials can be used as both the matrix and fillers of the shielding materials.

2.1 Carbonized Waste Materials for EMI Shielding

Due to the high electrical conductivity carbon-based materials are very much superior candidates in the EMI shielding materials. As a result of the lack of fabrication methods and involvement of toxic and expensive materials, it is difficult to scale the production of carbon-based EMI shielding materials. In the perspective of waste to wealth approach, biomass materials are gaining much importance in the development of EMI shielding material since it paves a new path of developing economic, sustainable and environment friendly carbon-based EMI shielding materials. Thus, biomass resources serve as the best alternative for the scalable and sustainable development of EMI shielding materials [23]. Straw is an agricultural waste which is mostly disposed and burning of it can create air pollution as well as health problems for human. Xiaohui Ma et al. converted this biomass waste material into the form of an EMI shielding material. They have fabricated straw-derived hollow porous carbon-tube arrays (SCAs) through the ordered assembly of directly carbonized wheat straw. Self-carbonized wheat straws were fabricated by pyrolyzing the wheat straw in the presence of flowing high-purity nitrogen at different carbonization temperatures [23].

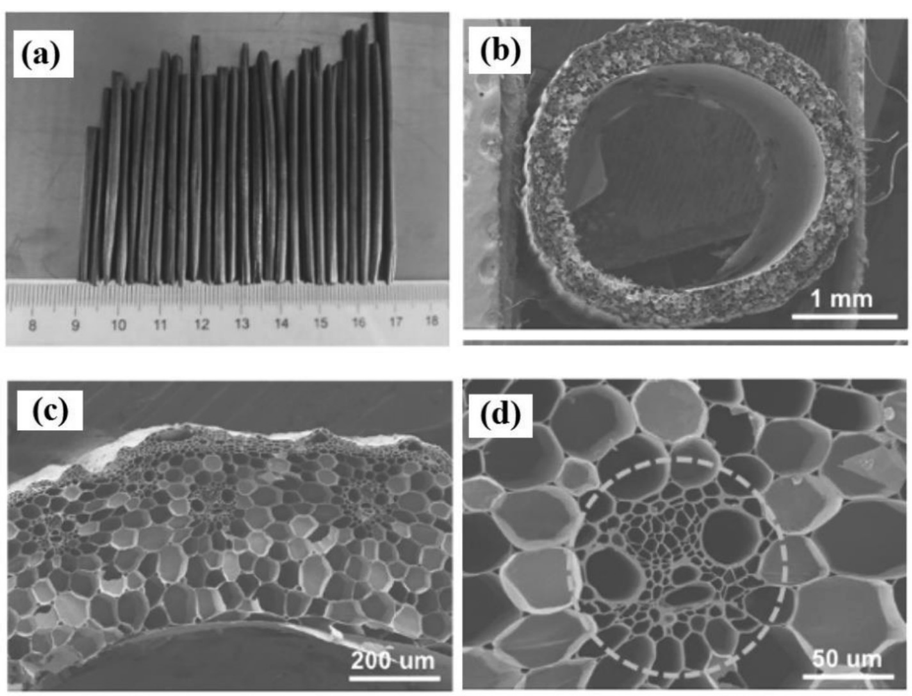

Fig.1 (a) Optical image of self-carbonized wheat straw; (b), (c) and (d) SEM images of self-carbonized wheat straw, Reprinted with permission from [23].

The material had highly porous structure as shown in Fig. 1(b), 1(c) and 1(d). Since the straw was carbonized the conductivity of the material got enhanced and hence the shielding efficiency (SE). The

EM waves suffer reflection loss as well as conductive dissipation as it enters the materials [23].

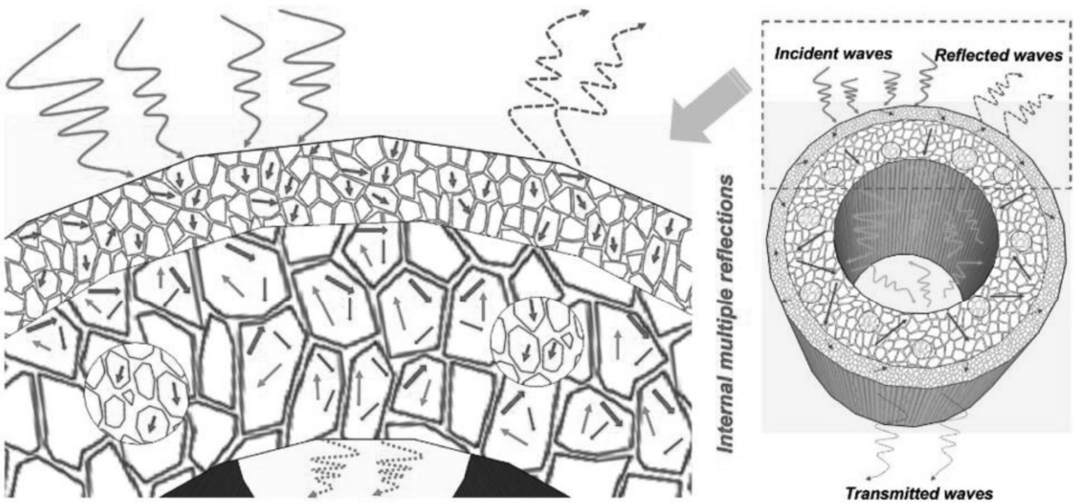

Fig. 2 Schematic representation of shielding mechanism of the hollow structure by multiple internal reflections, Reprinted with permission from [23].

Also the porous hierarchical structure contributed multiple reflections and hence the material had strong shielding efficiency of 57.7 dB which is shown in Fig. 2. The hollow interior of the straw enabled the filling of suitable material into it and hence modified the SE further. In this study, they have filled graphene aerogel in the interior and the EMI SE could be upgraded to 70.6 dB. The porous nature of graphene aerogel and the interfacial polarization induced at the interface of graphene aerogel and inner surface of straw altogether contributed to the SE of the material. This study portrayed how a waste material can be converted into an extremely functional material [23].

Zhongyi Bai et al. also developed a light-weight and highly efficient EMI shielding material based on waste straw porous carbon. Porous carbon is an efficient candidate among EMI shielding materials. Carbonaceous biomass also finds applications due to their light weight and good electrical conductivity. Zhongyi Bai et al. adapted the potassium hydroxide (KOH) activation method for the preparation of straw carbon (SC) materials with specific surface areas and mesoporous structure. This material suppressed EM radiations effectively by absorption dominated mechanism. The inherent dielectric loss of carbon material contributed to the absorption of electromagnetic wave and the impedance mismatch of the material got improved by the porous structure. Defects in activated SC generated many polarized centers and the porous structure of the material introduced multiple reflections and multiple scattering. The better electrical conductivity also contributed to the loss of EM radiation by conduction loss. SC prepared at 900°C had the maximum shielding efficiency of 47.58 dB with a thickness of 5 mm, thus a promising material for EMI shielding [24].

Sorghum straw is typically regarded as waste and burned in the fields, which contributes to some degree of atmospheric pollution. Reusing this biomass is a vital method to protect the environment and recover waste. Pengfei Yin et al. utilized this biomass to produce biochar and they have developed an EMI shielding material based on this biochar. Through a simple two stage calcination method, they could produce a unique biochar/ (Fe, Ni) hybrid with notable low-frequency microwave absorption ability. Biochar-based electromagnetic absorbing materials demonstrate effective microwave absorption characteristics in a rather high-frequency region, indicating the viability of using biochar to make effective electromagnetic absorption material. Due to the combined effects of interface polarization, dipole polarization, natural resonance, eddy current and conduction loss, multi-reflection and scatter, improved impedance matching, etc., this hybrid could show exceptional low-frequency microwave absorbing capabilities. To investigate the effect of biochar in the composite they have analyzed the dielectric, magnetic and EMI shielding properties of both biochar/ (Ni, Fe) and normal nickel ferrite (NFO) samples calcined at various temperatures. The inclusion of biochar with the metal nanoparticles could enhance the value of imaginary part of the dielectric permittivity (Ɛ”) which contributes to the loss of microwave within the material since Ɛ” represents the energy loss ability of a material. Also an improvement in the tangential dielectric loss could be observed which also illustrates the ability of the material to absorb EM radiations. The growth of grains and the release of stress in (Fe,Ni) NPs were greatly aided by the higher calcination temperature. This could also weaken the binding effect to encourage the development of the magnetic domain and lower the magnetocrystalline anisotropy constant, which resulted in the increase of magnetic permeability of the composite and hence contributed to the magnetic loss within the material. In contradiction to many hybrid materials, this material shows microwave absorption in low frequency range and with a small thickness also. This is a combined effect of many dielectric and magnetic phenomenon occurring in this biochar/(Fe, Ni) hybrid material [25]. This study offers a novel method for producing low-frequency electromagnetic absorbers while protecting the environment and promoting sustainable development through the use of renewable biomass.

Gokcen Akgul et al. developed EMI shielding composite with biochar and iron. This study investigates the EMI shielding ability of biochar-iron composite derived from tea waste. Biochar is a carbonized material which is produced from the pyrolysis of biomass in inert atmosphere. Biochar-iron composite were prepared by the simple method of impregnation of ferric chloride at desired amount with tea waste and followed by pyrolysis at inert atmosphere. This composite was then encapsulated into PMMA to synthesize the shielding material. The reflectivity of the sample was found to be nearly 10 dB. Thus the biochar-iron composite derived from tea waste can be used as a sustainable, cheap and green EMI shielding material [26].

2.2 Waste wood-based EMI shielding material

The majority of waste wood used for domestic, commercial, or industrial purposes is burned in mixed waste forms or dumped in landfills. Significant amounts of cellulose fibers with exceptional mechanical qualities can be found in waste wood. This cellulose can be recycled and availed for various applications. Papers derived from this cellulose along with inclusion of suitable fillers can be used for the fabrication of EMI shielding materials. Jihyun Park et al. introduced graphene nanoplatelets (GnP) into waste wood cellulose and fabricated EMI shielding papers by a simple and effective method. The cellulose fibers were isolated from waste wood by alkali treatment and bleaching. Graphene nanoplatelets are conducting carbon material which consists of small graphene stacks and were added at different percentages into the cellulose as the conductive filler. The cellulose GnP papers were carbonized at various temperature to improve the electrical conductivity and thus to enhance its shielding efficiency. Electrical conductivity and shielding efficiency of the paper were investigated by varying the amount of GnP and overlapping different number of papers [27]. The electrical conductivity of the composite paper was zero at a carbonization temperature of 700°C regardless of the number of overlapping of papers. A gradual increase in conductivity was observed as the GnP content, the number of overlapping and carbonization temperature increases. Maximum value of conductivity was observed for 3 overlapped carbon papers with cellulose to GnP weight ratio 85:15 carbonized at 1300°C [27]. As in the case of conductivity, similar enhancement in the EMI shielding efficiency could be observed with increase in the GnP loading, number of overlapping and carbonization temperature. Maximum shielding efficiency of 72.5 dB was found for the sample with maximum conductivity in the X-band frequency range. The improved conductivity and the thickness of the paper played a major role in imparting such a great shielding efficiency to this paper. Thus, this carbon paper obtained from a waste wood material with proper recycling technique can be utilized for various applications such as military and civil applications, in signal filter parts, noise separation etc. [27]. Architectural timber elements will be created throughout the construction and demolition of buildings. Furthermore, a lot of scrap wood is produced by wood furniture companies and other industries. Beyond the construction of buildings, more functional applications of waste wood is being explored since it's a biomass resource whose recycling will be a great path to develop various sustainable materials. It is a great source of carbon with a good graded porous structure. Waste wood can be effectively modified into electrically conducting material by carbonization at high temperature. Thus, wood derived carbon (WC) materials can be a candidate for fabricating light weight EMI shielding materials. Xiaofan Ma et al. investigated the relevance of lightweight and porous WC for developing shielding material since lightweight shielding materials are extensively required in aerospace, portable and wearable electronic devices. Since the density of a material plays adequate role in its shielding efficiency, they have studied the shielding performance of three woods; balsa wood, basswood and beech which differ in their density. A detailed analysis on various factors such as carbonization temperature, cross section of the wood and thickness of the sample on the SE were carried out. The carbonization of the wood made it conductive and a large number of free electrons in the conductive skeleton of carbonized wood cause conduction loss of the EM radiation. The highly porous structure of the carbonized WC also contributes to the shielding of EM waves. From the detailed study of the three woods, it could be observed that for same carbonization temperature and thickness, the wood with high density and longitudinal section has the maximum shielding efficiency. Apart from EMI shielding this material possessed self-cleaning and thermal insulation properties as well. As the carbonization temperature increased, an elevation in the contact angle of WC from all three woods was observed and thus the hydrophobicity of the materials got improved. This material proves to be appropriate to replace non-renewable and high-cost EMI shielding materials [28].

2.3 Recycled waste tissue paper-based carbon aerogel for EMI shielding

Carbon aerogels (CAs) are multifunctional materials which are widely explored for their high porosity, low density, high electrical conductivity and chemical inertness. Many researchers have fabricated CAs using biomass materials such as wood cellulose, bacterial derived cellulose and waste paper etc. The major challenge in the fabrication of CAs in this method is the difficulty in attaining all the essential properties in a single material. Waste tissue paper (WTP) is a biomaterial which is abundant of carbon in the dry form. Recently Linsha et al. reported that they have successfully synthesized CAs from WTP using a mild method. They have used polyvinyl alcohol (PVA), which is a nontoxic and low-cost polymer as the cross-linking agent in the fabrication of CAs. Addition of PVA established strong cross-linking between the cellulosic structures of WTP and which resulted in the formation of WTP-PVA CAs with sufficient mechanical strength along with good electrical conductivity and thermal stability [29].

The WTP-PVA aerogel was initially prepared by freeze drying method and then it was carbonized to make the CA. In the case of this aerogel, since the material consisted of large number of pores it could easily give rise to impedance matching between the medium and the shielding material. Hence reflection was not the prime mechanism for EMI shielding in WTP-PVA CAs. It was observed that this aerogel has a conductive network with large numbers of graphitic and non-graphitic domains. The high electrical conductivity leads to conduction loss within the material and the dielectric loss or the relaxation loss was attributed to the functional groups, defects and interfacial polarizations at the graphitic and non-graphitic interfaces [29].

The porous structure trapped the EM waves inside the shielding material and the waves undergone multiple reflections at the walls of the cell and hence the EM wave got completely dissipated into the form of heat before it got transmitted from the CA. The aerogel exhibited an absorption dominated shielding mechanism with a maximum SE of 40 dB. The function of WTA-PVA CA was not limited to EMI shielding. It also served as a good absorber of CO_2. Porous carbon materials are potentially used for CO_2 absorbing applications which usually require some chemical activation or modification processes. WTA-PVA CA had generous CO_2 uptake ability without any chemical modifications due the presence of large pores, high surface area and the presence of hydroxyl group on its surface enabled the formation of strong hydrogen bond with the highly electronegative oxygen atom of CO_2 molecule. Also, the availability of large percentage of ultramicropores, with diameter ~0.5nm to 0.7nm, suitable for filling CO_2 molecules which have kinetic diameter ~0.33nm can be a possibility of better CO_2 absorption performance of the material. This type of materials can bring huge impact on technology due to their multi functionality and sustainability [29].

A. Uddin et al. reported a sustainable method of fabricating green shielding material with waste tissue paper. The prime requirement of a superior shielding material is the large effective absorption with minimum secondary reflection. To design such materials, specific microstructural materials are required with ability to independently tune the absorption and reflection causing factors, polarization loss and conduction loss respectively. In order to achieve these specifications, they have incorporated 2-dimensional molybdenum disulfide (2D MoS_2) into waste cellulose paper by simple soaking and carbonization techniques. The characteristic properties of 2D

MoS_2 such as high surface area, numerous defects and unique polymorphism could substantially generate many interfaces within the material and thus could enable polarization. Also, the integration of 2D MoS_2 in to the waste tissue paper could introduce a continuous conductive network within the hybrid material. Its high surface area could help to achieve an effective contact with the cellulose fiber and thus provide better shielding efficiency with low filler amount as compared to 1-dimensional materials. The better dielectric losses due to increased interfacial polarization and the conduction loss cooperatively imparts the EM shielding property to the material with absorption loss of ~-15 dB and a total shielding efficiency of ~-28 dB with green shielding index g_x=1 [30].

2.4 Water Hyacinth based activated carbon composite for EMI Shielding

Water Hyacinth is a floating aquatic impenetrable weed which may obstruct the navigation. Water Hyacinth reduces the light and oxygen transmission and it will affect the aquatic life. The proper management of Water Hyacinth can be beneficial in multiple aspects. Organic materials are widely explored for their ability to generate activated carbon. Water Hyacinth is also abundant with cellulose which can be utilized as a base for obtaining activated carbon [31]. Azam et al. investigated the effect of carbonization temperature of Water Hyacinth on electrical conductivity and EMI shielding property in Water Hyacinth/phenol-formaldehyde (PF) polymer composite. For this they have carbonized the stems and leaves of Water Hyacinth at various temperatures and mixed it with PF resin to derive the polymer composite. The composition was maintained as 30% Water Hyacinth activated carbon powder in 70% PF resin. By the structural analysis of Water Hyacinth they could observe that it had sponge like pore structure. At the carbonization temperature of 500 ^{0}C Water Hyacinth had the lowest electrical conductivity of 3.10-7 S/cm. However, it possessed high transmission shielding effectiveness value of 12.7dB at this temperature due to the influence of KCl in it. By increasing the carbonization temperature of Water Hyacinth more pores gets opened and improved the crystal structure of carbon. This caused an increase in the electrical conductivity of the composite. Thus the reflection and multi reflection in the composite got increased which lead to enhancement in total shielding effectiveness. In this study they emphasized that the Water Hyacinth biocarbon have high air volume fraction due to wide pore structure. It enables absorption of electromagnetic wave and reduces the surface reflection. And they could successfully develop EMI shielding material from Water Hyacinth composite with highest EMI SE 41.15 dB (attenuation 99.99%) at frequency of 8 GHz [31].

2.5 Loofah Sponge Based Material for EMI Shielding

Natural loofah sponge serves as a substrate material with porous network for numerous applications. Infusion of conductive materials into loofah sponge can make it appropriate for electronic applications. Songtao Li et al. obtained a multifunctional composite with carbonized loofah sponge (CLS), phenol-formaldehyde resin (PR) and silicon carbide (SiC). The SCLS with 3D porous network structure shows superior electromagnetic shielding performance and desirable mechanical properties. In the composite PR acted as a shaping agent and SiC as the structuring agent. SCLS was synthesized by curing the natural loofah sponge immersed in PR by hot pressing followed by pyrolysis at high-temperature as depicted in Fig. 3. The natural porous structure of loofah is much advantageous and the introduction of SiC imparted better mechanical stability and shielding ability to the composite [32]. Detailed analysis of the samples was done to identify the various properties of the composite. The flexibility of the natural loofah sponge was retained in the composite since the PR is coated only on the surface of the loofah. Conductivity of the SCLS was found to be more compared to CLS due to the improved stacking of the conductive carbonized loofah fibers and the decrease in distance between the conductive paths. The shielding property and mechanical property of PR coated loofah sponge after carbonization got improved with the incorporation of SiC. The average EMI shielding efficiency of the sample was found to be 68.4 dB. In addition, the composite exhibited good thermal insulation and thermal stability [32].

Liang Liu et al. developed a microwave absorbing material with loofah sponge derived hierarchically porous carbons. They have prepared the loofah sponge derived carbon/cobalt ferrite ($CoFe_2O_4$)

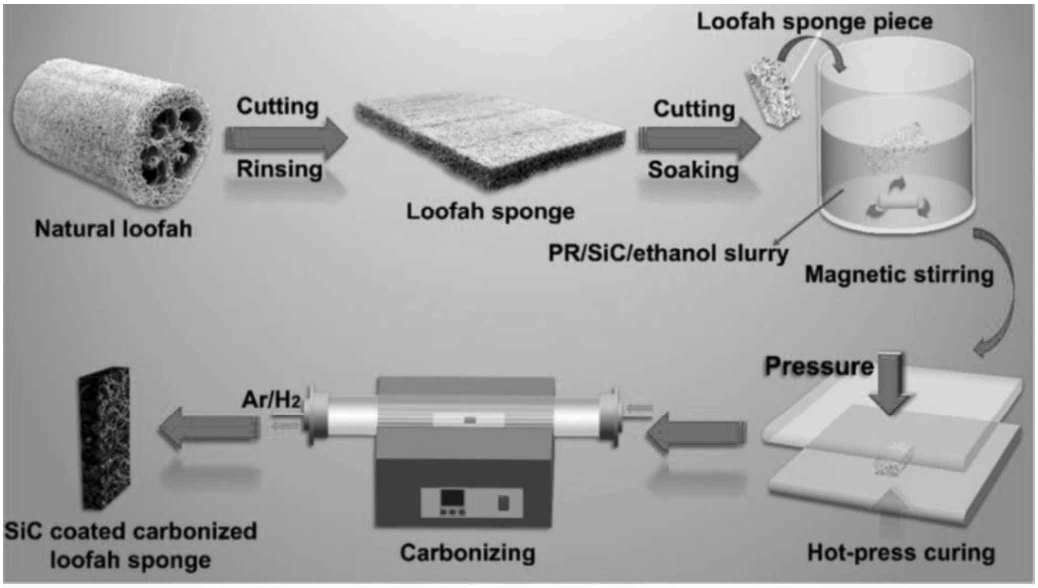

Fig. 3 Schematic representation of the preparation of SiC coated carbonized loofah sponge, Reprinted with permission from [32].

composite by functionalization and pyrolysis treatment as depicted in Fig. 4 (a) and (b). The porous composite exhibited a structure similar to lotus root and with low density (Fig 4(c)). The temperature of pyrolysis was found to affect the conductivity of the composite. As the temperature of pyrolysis increased the functional groups containing oxygen were reduced which resulted in the formation of enlarged domains of π-conjugated C=C double bonds. Hence, the area of connected sp^2 C=C conductive path increases and higher electrical conductivity is imparted to the composite [33].

The improved electrical conductivity allowed the transport of free electrons within the lotus root like structure. This permitted the electrons to align according to the incident electric field and thus increased the polarization and hence permittivity. The Joule heat of electricity due to the movement of electrons under the influence of electromagnetic field also contributed to the loss capacity of microwave. The high microwave absorbing property of the composite is attributed to the synergistic effect of carbon skeleton and $CoFe_2O_4$ nanoparticles. The new interfaces developed between the carbon skeleton and $CoFe_2O_4$ introduces interfacial polarization relaxation loss due to improved relaxations and resonances.

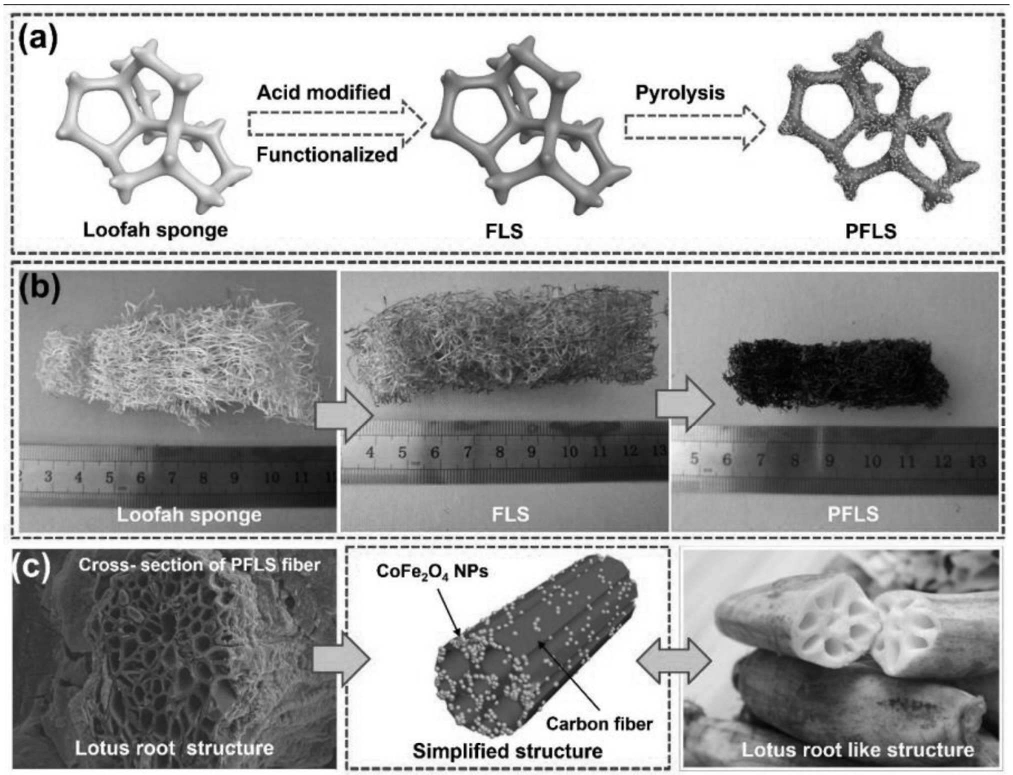

Fig. 4 (a) Fabrication of loofah sponge derived porous carbon, (b) images of loofah at different stages and (c) structure of the composite, Reprinted with permission from [33].

The structural peculiarity of the composite also played a key role in the microwave absorbing ability of the composite. The lotus root like morphology with internal channels and rough surface caused scattering to the microwave and hence attenuated the microwave by multiple internal reflections. The structure enlarged the propagation paths of EM waves which also resulted in effective attenuation of EM waves. Thus, this composite serves as an efficient candidate among low cost and light weight EMI shielding materials [33].

2.6 Waste rock wool – reduced graphene oxide (rGO) composite for EMI shielding

An enormous quantity of waste rock wool (RW) was created as building and excavation activity increased. The disposal of this on land is creating serious environmental issues. Recently waste rock wool is being used for developing various functional materials such as filter bed, heavy metal-ion absorbent and for oil water separation. This can reduce the difficulty in recycling it to a large extent. Waste rock wool can be modified into a multifunctional EMI shielding material by incorporating graphene oxide by dip coating. The process is initiated by the synthesis of graphene oxide by the method of Hummers method. Graphene oxide is allowed to get deposited on the wool fibers by dip coating and then graphene is reduced by using hydrazine hydrate which is depicted in Fig. 5 [34].

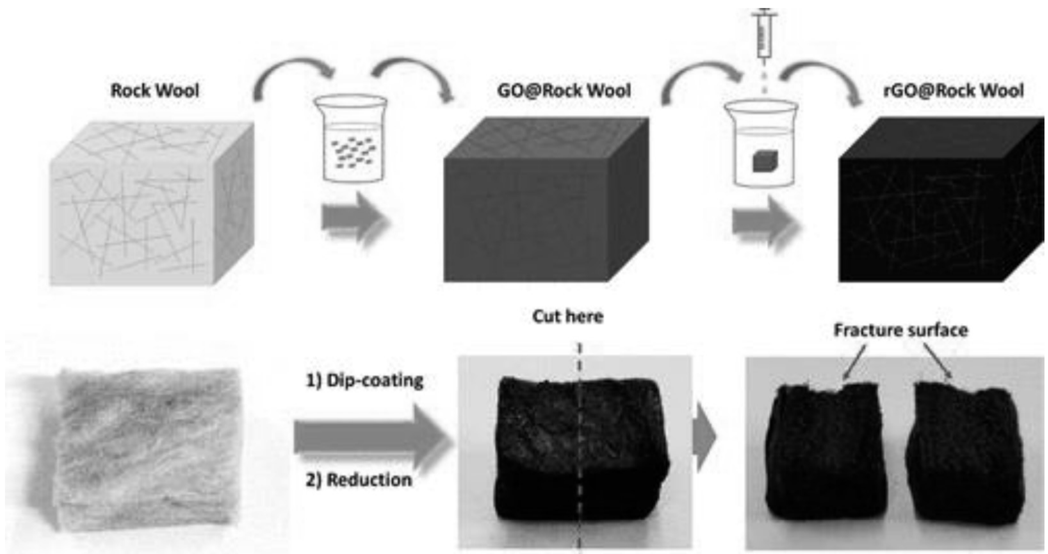

Fig. 5 Fabrication process of RW-rGO composite. Reprinted with permission from [34].

rGO develops a three-dimensional conducting network within the material and thus makes it suitable for EMI shielding. The rock wool rGO composite prepared using a 7mg/ml GO suspension has the highest value of electrical conductivity 2.1 S/m and EMI shielding efficiency of ~30dB in the X-band. The material has absorption dominated shielding mechanism which is resulted from the highly porous structure of the composite material. This porous structure also helps to diminish the impedance mismatch of the material and thus to nullify the reflection of EM radiations. The radiations entering the rock wool – rGO composite undergo multiple internal reflections as well as conductive dissipation. The absorption of the radiations also gets enhanced by the dipole polarization and directional polarization caused by the defects formed in the graphene oxide during the reduction process. Along with EMI shielding this unique material is hydrophobic and possesses thermal insulation and fire resistance. The characteristic hydrophobic nature of the rGO along with the roughness of the surface of the material makes the composite hydrophobic. The highly porous morphology of the material permits to trap the air within it and which is the reason for its thermal insulation property. This multifunctional material can be appropriate for numerous applications [34].

3. Conclusion and Future Outlook

One of the main factors which gives a negative aspect for the industrialization and modernization of the world is the uncontrollable increase in pollution. Proper attention is not taken for the disposal of waste materials. The damage caused by this waste on environment is enormous. People do not use appropriate techniques for the disposal or recycling of the waste materials. EMI is also a major risk even to human which should be controlled carefully. For the proper growth and development of our world, pollution control should be considered seriously. The prosperous future of our world will be incomplete without sustainable development. One best solution for the EM pollution is the fabrication of EMI shielding materials which are environmental-friendly. Plastic materials used for shielding purpose will also be turned into electronic waste. Thus, recyclable waste materials can be a promising material for this purpose. This article enlightens the recent researches for developing shielding materials from waste. Some of the simple and effective methods are discussed in this manuscript. This article focuses and emphasizes on the sustainable waste materials which are commonly available and most suitable for the EMI shielding application. Similar studies are present based on polymeric or synthetic waste materials which are not discussed in this review explicitly. These studies based on various kinds of recyclable waste materials are listed in Table 1. In future more biomass waste materials could be explored and converted as shielding materials. New technologies should be developed to fabricate these types of shielding materials in large scale and cost effectively

S. No	Material	Shielding Efficiency	Frequency	Reference
1	Biochar – Iron Composite	~10dB	8-12 GHz	[26]
2	Hybrid nonwoven recycled from carbon fibre waste	-85dB	8-12 GHz	[35]

S. No	Material	Shielding Efficiency	Frequency	Reference
3	Composite from waste rock wool	-25dB	8-12 GHz	[34]
4	Carbonized waste corru-gated boards reinforced with epoxy	-46 to -82 dB	8-12 GHz	[36]
5	Silver nanowire decorated recycled cigarette filters-based epoxy composite	-40dB	8-12 GHz	[37]
6	Recycled carbon fibre reinforced polymer composite	-40 dB	8-12 GHz	[38]
7	Carbon aerogels from waste tissue paper	-40dB	8-12 GHz	[29]
8	Straw derived carbon material	-57.7 to -44dB	8-12 GHz	[23]
9	Carbon nanotube/Grou-nd tyre rubber composite	-66.9dB	8-12 GHz	[39]
10	Pyrolized cork-geopolym--er composite	-13.8 to -15.9 dB	8-12 GHz	[40]
11	Leather solid waste/PVA Silver paper	-50 to -90 dB	8-12 GHz	[20]
12	Loofah sponge derived porous carbon/ CoFe2O4 composite	-43.8dB	8-12 GHz	[33]
13	SiC coated carbonized loofah sponge	-68.4dB	8-12 GHz	[32]
14	Polyaniline/Red mud composite	-33 to -41 dB	8-12 GHz	[41]
15	Water hyacinth activated carbon powder/PF resin	-41.15dB	8-12 GHz	[31]
16	Waste wood cellulose composite paper	-72.5dB	8-12 GHz	[27]

Table 1: Comparison of EMI SE of shielding materials derived from recycled waste materials.

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