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Sustainability in Electromagnetic Metamaterials: Synthesis, Applications, and Future Directions with Challenges

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Abstract-: This paper is about sustainable Electromagnetic Metamaterials (EM-MM), which are a new class of artificial materials with unique electromagnetic properties that cannot be found in nature. These materials are made from discrete micro and nanoscale objects which resonate, allowing for precise control over how they interact with electromagnetic waves, and hence, leading to unheard of functionalities. Thus the need for sustainable synthesis methods for EM-MM has become paramount to mitigate the quantity of resources associated with conventional fabrication techniques. Renewable resources like biopolymers that mimic natural patterns are examples of the sustainable use of bio based synthetic material pathways. This may guarantee sustainability through fabricating additive manufacturing strategies, especially 3D printing innovation where fabric statement is controlled only as required, diminishing waste. With all this recycling and up cycling offer opportunities for development and cost reduction while reducing the natural impacts related to sustainability. There are several different domains have benefited from the application of EM MM, for example solar energy harvesting offer potential for sustainable power generation, imaging uses met material lenses which have superior resolution and sensitivity, while in telecommunications met material antennas ensure to transmit and get signals more successfully. But there are still a few issues that still need to be resolved in electromagnetic met materials. Future directions include the research of incorporating a plan of new types of electromagnetic composites with upgraded qualities and sustainable synthesis strategies. Applications of technology require to overcome practical challenges such as integration, toughness, and cost-effectiveness while assessing societal implications, financial, and social

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affects. For the sustainable advancement of metamaterials in order to deal with major societal concerns, minimizing their natural impressions requires collaboration and moral concerns.

Keyword-: Electromagnetic metamaterials, solar energy, synthesis, 3d printing, recycling, antennas, nanomaterials, sustainability, environmental impact, telecommunication.

1 Introduction

Artificial EM-MM have properties that are not shown by naturally occurring materials. They are designed to have specific electromagnetic characteristics like negative refractive index, allowing them to twist light in unconventional manners. As a result, they have wide applications including renewable systems [1]. "Metamaterial" basically this term comes from the Greek words "meta and material" though Meta implies above or beyond usual, reordered, changed, or inventive. It is impossible to get metamaterial from any persistent and homogenous medium, subsequently all of them are composites. Normally, metamaterials comprise discrete resonant microscale and nanometer-scale objects that act as minor atoms and atoms in normal substances concerning their electromagnetic response to light and other forms of energy [2]. Left-handed, backward wave media, negative index materials, or double-negative materials are another name for metamaterials. Metamaterials have characteristics like idealized lensing, classical electromagnetically induced transparency, cloaking capability, high-frequency magnetism, dynamic modulation of Terahertz radiation, reverse Doppler impact, and reverse Cerenkov phenomenon [3]. Based on permittivity and permeability the MM are classified as mu-negative fabric, epsilon-negative material, double-positive material, and double-negative material. The mu-negative fabric and epsilon-negative material are also called single negative materials. The others incorporate the double-positive and double-negative materials designed at particular frequency bands [4]. It's interesting to note that chirality is important for biosensors that use plasmonic materials and function with biomolecules. New biomolecule based chiral metamaterials are promised to have prevalent resolution and a wide range of plasmonic collections. Also, this type of material can realize negative refractive index, light polarization control, reconfigurable chirality, stimuli-responsive behavior, and chirality-detecting. These kinds of metamaterials are very useful for purposeful tasks [5]. The utilization of biomolecules for optical metamaterial engineering ensures the effectiveness of these tools and gadgets with natural situations. In expansion to their biocompatibility, MM which are based on biomolecule offer other benefits, such as tall tunability through objects, affordable, basic, and flexible manufacturing without affecting the quality [6]. In this paper, we study about the electromagnetic metamaterial's sustainable synthesis, the application of metamaterials, and its future directions and challenges.

2 Sustainable Synthesis Methods for Electromagnetic Metamaterials

Engineered electromagnetic properties have captured the creative ability of researchers and engineers in electromagnetic metamaterials, making them curious for utilize in different areas such as telecommunication, imaging, and energy conversion. Numerous of the conventional procedures for synthesizing these materials are resource-intensive, ecologically unsafe, and financially short lived. This has provoked scientist to investigate other ways of synthesizing

such valuable materials that can offer assistance to meet not as natural concerns but moreover progress their productivity as well as reduce the cost of manufacturing metamaterials.
A promising and possible region that research is taking on is utilizing bio-based precursors in the synthesis of metamaterials. Bio-inspired methods imitate nature's design principles like self-assembly and biomineralization to make metamaterials with custom-fitted electromagnetic responses [7]. For example, chitosan and cellulose have been utilized as templates for the advancement of electromagnetic metamaterials with progressed mechanical properties as well as biodegradability utilizing biopolymers. By utilizing renewable resources and biocompatible material such synthesis routes give a sustainable alternative to conventional fabrication methods [8]. Apart from biobased materials, the application of green chemistry standards in metamaterial production has been recognized as a key technique. Green Chemistry is aimed at designing chemical processes that diminish the utilization and generation of unsafe substances, minimize energy utilization, and maximize resource utilization [9]. In numerous cases, green synthesis approaches towards electromagnetic metamaterials include solvent-free or aqueous-based strategies to eliminate the usage of poisonous natural solvents.
Moreover, additive manufacturing technologies, particularly 3D printing show assurance for sustainable creation of electromagnetic metamaterials [10]. Additive manufacturing permits material testimony to be accurately controlled hence permitting the designing and manufacturing of complex metamaterial structures with minimum waste materials [11]. This innovation also empowers on-demand production and customization through which productive resource utilization is accomplished while decreasing the requirement for large-scale fabricating facilities and this promotes sustainability in material synthesis [12]. We take filaments which are available at market as printing materials, i.e., the polylactic acid (PLA) and the Electrify as shown in Table 1. Specifically, 3D printing has already been utilized in creation of dielectric microwave components & metamaterials [13].

Table 1: Printing parameters for PLA and Electrify filaments [13]

Parameters	PLA	Electrify filament
Diameter of Filament	1.75 mm	1.75 mm
Conductivity of Filament	0 S/m	104 S/m
Diameter of Nozzle	0.4 mm	0.4 mm
Temperature of Nozzle	230°C	140°C
Temperature of Printing Bed	110°C	Room temperature
Speed of Printing	25 mm/s	15 mm/s

Among other approaches, sustainable synthesis can also be carried out by recycling and upcycling materials. In this way, analysts can minimize the natural impact of extracting crude materials and their disposal by changing them into waste from different firms. For example, modern researchers have looked into utilizing waste plastics and metals to create electromagnetic metamaterials this suggests that recycling can be part of sustainable synthesis [14]. Additionally, there are upcycling approaches aimed at expanding the value of low-value items making them high-value ones in arrange to upgrade sustainability in metamaterial fabrication processes [15]. Fig. 1 contains the synthesis methods of EM MM. These approaches not only address environmental concerns associated with conventional synthesis methods but also offer opportunities for innovation, cost reduction, and wide range of societal benefits.

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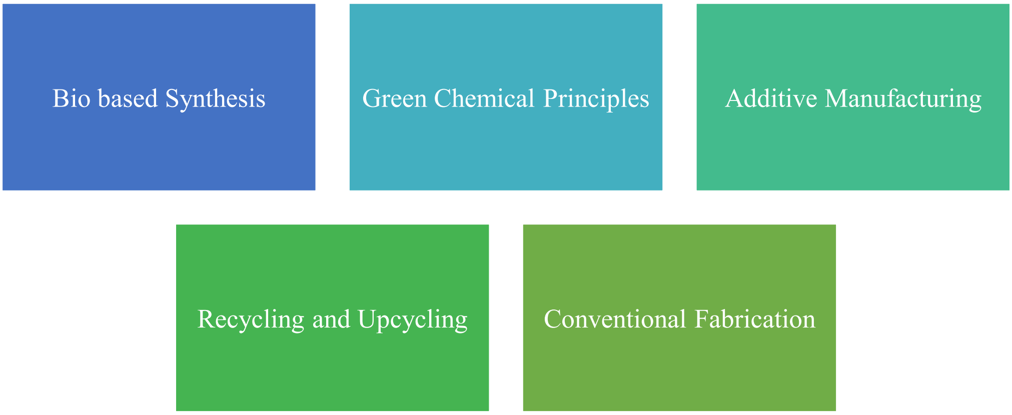

Fig. 1: Synthesis Methods to Sustainable Electromagnetic Materials

3 Applications of Sustainable Electromagnetic Metamaterials

The effectively prepared EM-MM have a variety of applications in different areas stemming from their special and designed electromagnetic properties. Sustainable Electromagnetic Metamaterials have found usage in multiple spaces including, telecommunications, imaging, energy harvesting, and natural detecting [16]. One of the most fascinating fields where there has been a part of interest in electromagnetic materials is solar energy harvesting. These intelligent materials may provide a different path to extremely effective solar cells by precisely controlling light absorption and conversion to power [17]. The researchers utilizing metamaterials have accomplished remarkable leads over conventional solar cell efficiencies by deliberately controlling light absorption and scattering [18]. For example, META Materials Inc., a pioneer company has already scaled up this idea into production by the use of metamaterials in solar energy film. These films, through their compelling light collection and absorption, lead to higher efficacy [19].

The utilization of electromagnetic metamaterials is progressively being seen in telecommunication sectors for the development of more productive antennas for transmission and receiving signals. All this progress results in wireless communication systems that are more efficient, making it useful for a variety of purposes. The primary goal has been to create an antenna with a small size, significant bandwidth and higher gain, as well as numerous antennas at the transmitter-to-receiver connection to increase channel capacity [20]. The development and innovation of fresh and new concepts and productivity methods in metamaterials, suitable for the use of it in antenna designs [21]. Table 2 shows the performance advancements of antenna due to metamaterials. Along these lines, advanced imaging tools cannot be developed without eco-metamaterials which have the capability to provide greater resolution and sensitivity. These lenses work by manipulating electromagnetic waves below the wavelength scale; hence, they can greatly enhance imaging performances in microscopy, medical imagery or remote sensing [22].

Table 2: Comparison between antenna designs with its alternative designs [26]

Size calculated in (W × L mm²)	Functional Frequency Range (GHz)	Method or Technique	10-dB BW (%)	Maximum Gain in (dBi)
27.00 × 33.00	3.20–14.00	Metamaterial	126	3.90
40.00 × 20.00	3.00–11.00	T-shaped ground	114	5.00
17.60 × 33.60	3.20–10.96	- - -	110	3.30
12.00 × 22.00	3.10–11.10	Slots	114	4.00
40.00 × 40.00	3.10–11.00	Vivaldi antenna	114	7.06
14.50 × 22.00	3.08–14.10	NZRI/SNG metamaterial	128.3	6.12

Another promising region for utilizing sustainable electromagnetic metamaterials is energy harvesting. This could be achieved through unique plans of metamaterial structures that could trap and convert electromagnetic energy from surrounding sources like solar light, radio waves, and Wi-Fi signals consequently viable in terms of power generation [23]. This way electromagnetic metamaterial plays a major part in building a more sustainable energy environment with the assistance of these metamaterial-based devices that utilize renewable energy sources and are made from eco-friendly materialss [24].

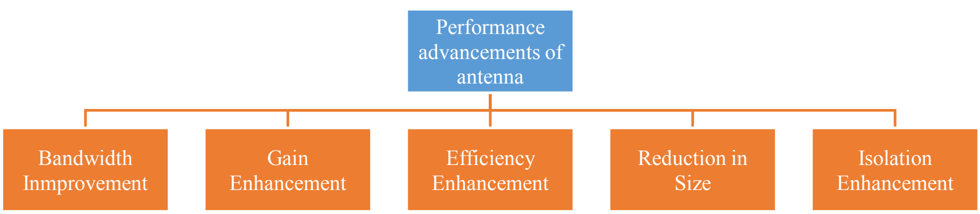

Fig. 2: Performance improvements in antenna when using metamaterials

Moreover, the future usage of sustainable electromagnetic metamaterials may incorporate cloaking devices, and quantum technologies, among others. For example, Cloaks utilizing Metamaterials have the potential to manipulate electromagnetic areas and cause things to become undetectable at specific wavelengths, this has a wide range of use in military practices such as camouflage [25]. The requirement for sustainable synthesis approaches emphasizes the expanding sustainability focus inside defense and security application systems that apply to these cloaking devices. With the growing request for eco-friendly innovation, it is anticipated that sustainable meta-materials will progressively shape different industries' future as shown in Fig. 2.

4 Future Directions and Challenges in Sustainable Electromagnetic Metamaterials

Towards sustainable electromagnetic metamaterials, future directions and challenges have risen, forming the direction of this field. In these categories, there are various perspectives such as materials design, synthesis methodologies, technological applications, and broader societal suggestions that contribute to the changing scene of sustainable metamaterials research. One key future direction is in designing new feasible materials with custom-made electromagnetic properties. While bio-based metamaterial has been successful so far in fabrication, there is more research into sustainable substitutes, including recycled or upcycled materials, which could increase the pool of precursors that are accessible [27]. The advancements in nanomaterials synthesis methods including bottom-up assembly and atomic layer deposition enable control over fabric properties as well as structural plans thereby permitting the creation of improved adaptations of next-generation sustainable metamaterials [28]. Table 3 is showing the characteristics and morphology of nanoparticles synthesized using various techniques.

Table 3: Characteristics and morphology of nanoparticles synthesized using various techniques [35]

Nanomaterials	Synthesis Techniques	Features of Morphology	Properties
Metal oxides and hydroxides	Different techniques	Large surface area and redox qualities	Appropriate for electrochemical (EC) gadgets
Conducting polymers	Different techniques	Higher conductivity and adjustable redox potential	Adaptable for use in EC processes
Hybrid materials	A mixture of the kinds of nanomaterials	Improved performance and functionality	Improved qualities as a result of cooperation
0D nanoparticles and nanodots	Different techniques	Compact size, large surface area	Promising in terms of supercapacitors, batteries, sensors, and catalysts
1D nanowires and 2D nanosheets	Different techniques	Bigger surface area and superior conductivity	Ideal for fuel cells, supercapacitors, and other EC devices
3D nanostructures	Different techniques	High surface area, unique porosity	Possibility of fuel Cells, supercapacitors, and batteries
Nanomaterials for electrode materials	Different techniques	Customized parameters for highly efficient devices	Possibility of affordable EC gadgets

In EM-MM integrating sustainability considerations into the design of metamaterial synthesis methodologies remains a key challenge. To minimize natural impact amid the production of metamaterials green chemistry principles such as the usage of non-toxic solvents and energy effective processes are vital [29]. Accomplishing scalable and cost-efficient synthesis routes while making sure sustainability, is a significant issue. This will require intriguing collaboration between materials researchers, chemists, engineers, and ecologists to design an innovative synthetic process that will consolidate execution issues about both long-term sustainably and adaptability [30]. Another region where sustainable electromagnetic metamaterials can be implemented is technological applications. Metamaterial-based gadgets like antennas, sensors, and energy harvesters have been created to offer diverse societal needs including wireless communication frameworks, environmental observing tools as well as renewable sources of power [31]. However for these innovative advancements to convert to practical applications, they have to consider issues like integration into other systems (e.g., durability) with cost-effectiveness.

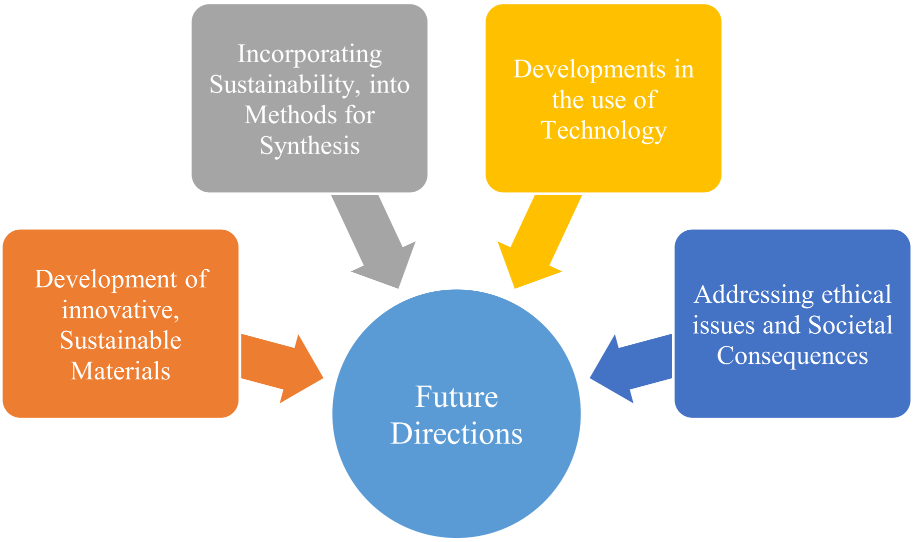

Fig. 3: Some Future Directions in Electromagnetic Metamaterials

Additionally, achieving accessible and reasonable sustainable metamaterial-based innovations for numerous communities within the world is necessary for promoting equitable advancement as well as resolving the issues related to global sustainability [32]. It is critical to consider wider societal suggestions of research on sustainable metamaterials since these are a few of the factors that foster dependable advancement and moral considerations. Throughout a product's lifecycle, it is critical to evaluate the possible effects that metamaterial-based technologies may have on society, the environment, and the economy [33]. The complete potential of sustainable metamaterials in addressing critical societal challenges while minimizing the ecological burden can be accomplished by considering improvements in materials design and synthesis methods, technological applications, and societal aspects [34]. Fig. 3 contains some future directions of metamaterials.

5 Conclusion

Electromagnetic metamaterials (EM MM) has shown a great promise for managing the societal challenges through its sustainable methods and innovations while reducing the impact on environment. This study consists various viewpoints of sustainable EM-MM highlighting below:

- Bio inspired synthesis methods offers a sustainable alternative to conventional fabrication techniques by leveraging the nature's design principles to produce met materials from natural resources like biopolymers. Additionally, green chemistry principles reduce the ecological impacts by using solvent-free or aqueous-based synthesis methods, this opens the door for the production of nature friendly met materials.

- Another technology is additive manufacturing technologies particularly 3D printing, it enables the accuracy control over material deposition, reduce the waste production and contribute to sustainability. Materials recycling and upcycling offers chances for cost reduction and innovations in met material fabrication processes and reduces environmental impacts.
- In the field of electromagnetic and met materials there are various applications across domains including solar energy generation, telecommunications, imaging, and energy harvesting. These materials enable improvements such as highly efficient solar cells, better wireless communication systems, and superior imaging technologies this contributes towards sustainable future.
- Future avenues of investigation could involve creation of new sustainable materials with specific electromagnetic properties; incorporation of sustainability aspects into the process of making them, tackling practical problems related to their use in technology. To address societal challenges while minimizing natural impacts it is necessary to realize the complete potential of sustainable metamaterials by interdisciplinary collaboration and ethical considerations.
- In summary of EM-MM we can say that it offers many applications, synthesis methods, innovative approaches and ethical considerations to get sustainability. By resolving challenges and grab the opportunities we can find the full potential of EM-MM and leading towards a societal change while taking care of the environment.

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