Sustainable Solutions in Sound Shielding: Harnessing Metamaterials for Acoustic Cloaking

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Abstract. The development of metamaterials promises to enable small-scale, worldwide industry-wide acoustic, electromagnetic, mechanical, and solar energy harvesting. Engineered structures surpass natural material limitations, offering capabilities unattainable in traditional counterparts. This paper explores metamaterials' manipulation of acoustic, electromagnetic, mechanical, and solar energy. Mechanical metamaterials convert strain into electrical energy, applicable from interstellar travel to terrestrial infrastructure. Precision-configured acoustic metamaterials efficiently harness dispersed acoustic energy, improving renewable energy methodologies. Integration into photovoltaic cells showcases metamaterials' solar potential, with innovative designs enhancing solar energy conversion efficiency. "Metamaterials" is a word used to describe artificial structures whose properties are based on the aggregate expression of individual components. Acoustic metamaterials are the term used for such constructions intended for the manipulation of acoustic waves. Controlled wave propagation is made possible by acoustic metamaterials, which is frequently not possible with bulk materials created chemically. This indicates that the wave propagation in acoustic metamaterials is directed and produces desired acoustic effects, independent of the mass-density properties of the material. The distinct properties of acoustic metamaterials have paved the way for the creation of practical solutions for a variety of uses, such as passive destructive interference, acoustic cloaking, sound focusing, low-frequency sound insulation, and biomedical acoustics. The kind of sound modification determines the general properties of an acoustic metamaterial. The properties of several of the most promising acoustic metamaterials from passive to active are introduced in this work. In order to achieve a sustainable future, it is necessary to combine environmentally

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friendly technologies with renewable energy sources for their final application. This is demonstrated by highlighting both the fundamental concepts and the physical models that were assessed.

Keyword-: Electron Beam Melting; Selective Laser Melting; Microstructure, Sustainability, Environmental Impact.

1 Introduction

Acoustic metamaterials have attracted significant wave-control properties, which may be utilized for applications in difficult acoustic settings [1]. The longitudinal nature of an acoustic wave is determined by two parameters: particle velocity (μ) and pressure (P). Table 1 illustrates the similarity between the transversal magnetic field and the auditory field under a two-dimensional (*2D*) harmonic stimulation. This demonstrates the equivalency in pertinent parameters required to produce meta-acoustic features. Analogous methods apply to the assessment of the synergy between the optical and acoustic components of metamaterials. The atomic and molecular configurations that make up macroscopic materials mostly determine their mechanical properties [2]. In a similar vein, the average of changing local fields may be applied to the resultant wave characteristics [3].

An acoustic cloak is a shell that encloses an item so that sound waves entering from any direction travel through and around it, rendering the object and the cloak "invisible" to the human eye. Since the elements needed are unusual and, as far as we know, not present in nature, we do not experience acoustic cloaking. However, acoustic cloaking is not physically limited in any essential way.

Conversely, metamaterials substitute artificial subscale repeating structures that mimic wave dimensions for the idea of molecular order. This enables precise control of the wave properties of an acoustic metamaterial by steering repeated unit cells to an output that is less dependent on material composition [4]. The size of the repeating unit cells in these formations varies with the acoustic application and result. However, the sub-wavelength local resonance components of an acoustic metamaterial may vary to the extent that the overall material response appears negligible. Since these acoustic metamaterials are dynamic carriers, even while the unit cells are constant, the local units may be seen in this way as a resonant frequency oscillator [5]. A single-mode approximation may be used to assess the trustworthiness of the efficient medium estimation, notwithstanding the negative elastic characteristics of phononiccrystals. By creating functional materials, acoustic metamaterials generally open up new avenues for creating customized acoustic performance. Unexpected capabilities made possible by acoustic. Meta material are often unattainable with normal materials [6].

1.1 Application of Metamaterials

In policy-oriented research, the term "sustainability" has gained traction as a symbol for the goals that public policies need to pursue [5, 6]. The core idea behind sustainability is that it is concerned with future generations' health, especially with regard to irreversible natural resources, as opposed to wellbeing, which is defined as meeting present needs. It is important to talk about how we may look at the idea of continuing a process or activity for a long period without causing harm to the environment. To prevent resource depletion and save future generations, this involves using resources wisely. This term, as it relates to technology, describes the development and application of technologies that, throughout the course of their whole life cycle, have minimal negative environmental effects. This entails minimizing their detrimental effects on the environment and utilizing them in the renewable energy sectors. These gadgets are often designed to be durable, energy-efficient, and to use recyclable or renewable materials. To build a sustainable future, renewable energy sources must be found and combined with eco-friendly technology for future usage [7].

Because of their distinctive designs, met materials have attracted researchers from a wide variety of domains, resulting in a diverse set of nomenclature [8, 9]. A few main types of magnetization may be identified according on how widely they are used for environmentally friendly purposes: acoustic, mechanical, chiral, and electromagnetic. "It is important to remember that, as noted on this page, surprising effects can be achieved with both three-dimensional metamaterials and two-dimensional structures known as metasurfaces or planar optics.

Electromagnetic materials, also known as negative-index metamaterials, are synthetic. Materials that are intentionally designed to contain extraordinary electromagnetic properties in addition to the electromagnetic properties of their constituents. Researchers have noticed these remarkable material properties that do not occur in naturally occurring compounds and have led to amazing discoveries in the field of electromagnetic engineering [6]. Most common materials have a positive refractive index. But the refractive index of the electromagnetic wave is negative in the MM in a certain frequency range. These materials have potential applications in electromagnetic shielding [10, 11], superlenses [11], and antenna design.

Gradient-index AMs: Owing to good impedance matching and acoustic energy dissipation within the gradient-index structures, gradient-index AMs are promising next-generation sound absorbing materials, which can enhance the sound absorption performance compared with common uniform-index AMs. The design and optimization of gradient-index structures for particular applications still need specific in-depth studies. On the other hand, the sound dissipation in complicated gradient-index structures could be further improved. Besides, the study on the topology of AMs may contribute to further illumination of the underlying mechanism of AM sound absorption.

Underwater AMs: Although the underwater experiments are more difficult and complicated than airborne experiments, underwater AMs are in great demand for anechoic coating of underwater vehicles.

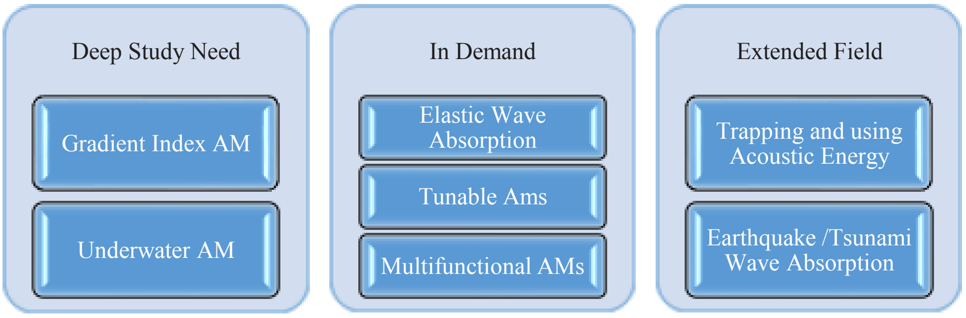

Fig. 1: Perspective for Acoustics Metamaterials.

Besides, most of the reviewed studies are only successful in the laboratory or in the initial stages of development. Although a company named Acoustic Metamaterials Group has started to develop metamaterials noise control technology, significant work remains to bring successful ideas (in a laboratory) into real-world applications because of the demand for adjustability, multifunctionality, and small size.

Elastic wave absorption: Previous work on elastic wave absorption should be continued with a consideration of the widespread presence of elastic waves (such as Lamb wave and Rayleigh wave).

Tunable AMs: An AM usually possesses a specific structure, and it is used for a specific application. Tunable AMs have the potential to be adopted for different applications by tuning the properties. The AMs may also be required to be tunable because of the subjectivity of the sound event perception.

Multifunctional AMs: In modern society, multiple functions are expected to be integrated into one device to save space and cost. For example, AMs with a combination of absorption and vibration suppression, absorption, and ventilation are in demand. However, those studies are just in the initial stages, and more in-depth investigations are expected. Nanoscale AMs: Nanoscale heat transport and nanoelectronics have important roles in nanoscale devices. Nanoscale AMs have the potential to reduce the amount of heat transport to ultralow levels.

Moreover, AM sound absorption can be broadened to save energy and reduce the damage caused by the power of nature.

Trapping and using acoustic energy: Theoretically, the acoustic energy in unwanted sound (such as noise) can be trapped, stored, and then exploited. The unwanted sound could be absorbed while the reuse of acoustic energy contributes to energy conservation. There are studies on the trapping of acoustic energy in which the absorbed acoustic energy is demonstrated to be converted to electrical current [8]. The reuse of acoustic energy needs further investigation. Power generation systems based on the reuse of acoustic energy are exciting and expected.

Earthquake/tsunami wave absorption: Although some countries, such as Japan and China, have earthquake/tsunami warning capability, attenuation of earthquake/tsunami wave is in demand to further reduce earthquake/tsunami damage.

The features of three-dimensional periodic metamaterials include acoustic, optical, mechanical, stimuli-responsive, and transportation applications. Upon deeper inspection, three-dimensional mechanical metamaterials seem to offer a lot of potential for use in filter and acoustic applications. The ability of these acoustic metamaterials to control and regulate sound waves surpasses that of conventional materials. In particular, metamaterials with negative or zero refractive indices for sound are fascinating because they may provide precise control over sound at subwavelength scales and provide new opportunities for acoustic imaging". Therefore, the wide range of three-dimensional periodic metamaterials presents an exciting exploration of uncharted scientific territory.

Multifunctional metamaterials are materials that display several, frequently unique features all at once that are not present in naturally occurring materials as shown above in Table 1. These substances are made to control sound waves, electromagnetic waves, and other waves in order to produce desired effects such superlensing, cloaking, and negative refraction. This is furthered by multifunctional MM, which combines various MM types to produce materials with many functions. For instance, MM that is intended to absorb electromagnetic waves can be coupled with MM that has a negative refractive index. An additional combination might include vibration control settings for energy harvesting material or possibility-sensing and absorption material. Spider silk, shells, and bones are just a few examples of natural materials that have hierarchical systems with elements throughout many length scales. Improved quasi-static mechanical properties that all display include high specific strength, stiffness, and hardness. With a hierarchy incorporated, elastic metamaterials may create periodic patterns that, with enough attenuation, can generate many wideband band gaps at various scale frequency ranges, including deep sub-wavelength regime. These extraordinary materials have already shown their worth in the field of sustainable development by advancing green energy projects, supporting biodiversity protection, and enabling high-tech filtering systems. It is not so difficult to form a more sustainable future where innovation and ecological stewardship coexist peacefully by using metamaterial technologies wisely.

Table 1: Mechanical properties of metamaterials.

Component	**Longitudinal wave velocities (m/s)**	**Density (kg/m^3)**
Matrix	340	1.29
Triangle scatterers	4670	2200
Coating	250	1340
Ellipse	2470	7960
Cylinder	5690	5060

2 Sustainable Materials for Noise Control

Recent years have seen an increase in public health and environmental awareness, which has sparked the creation of several innovative noise-cancelling materials as alternatives to conventional ones. These resources fall under two primary categories explained below:
A vast range of materials are reported in recent literature, ranging from the most widely used [8], [9], to the most peculiar solutions [10-11]. Additionally, a number of life cycle assessment (LCA) studies show that compared to glass fiber composites, natural fiber composites appear to be more economical, lighter, and environmentally friendly [12].

2.1. Natural Materials

Natural materials perform better at conserving energy the less processed they are; native materials must be used in order to lower the energy required for transportation. Furthermore, natural fibers have a detrimental effect on climate change due to their absorption of CO_2. However, additional characteristics must be taken into account. Compared to mineral fibers, vegetal fibers are less fire resistant and more vulnerable to fungal and parasitic attacks. It is also necessary to consider the non-toxicity of the chemical products employed in growing.

Sound Absorption-: Various natural materials possessing significant absorption capabilities, such coconut kenaf, flax, hemp, cork, sheep wool, or bamboo, can be used as sound absorbers or barriers in rooms. At 500 Hz, however, manufactured materials frequently have a greater absorption coefficient than natural ones. Expanded clay (more than 0, 80 in the 500-5000 Hz band) is another naturally occurring material that has significant sound absorption across a broad frequency range [15].
Impact Sound Insulation-: Probably the most popular application for a lot of natural materials is this (wood, cork, coconut fibers). Natural materials may be used to create resilient layers that improve impact sound insulation for floating flooring [18]. These panels function on par

with other conventional materials when fitted and configured precisely. The impact sound reduction for a few materials studied at the College of Perugia's Acoustics Laboratory.

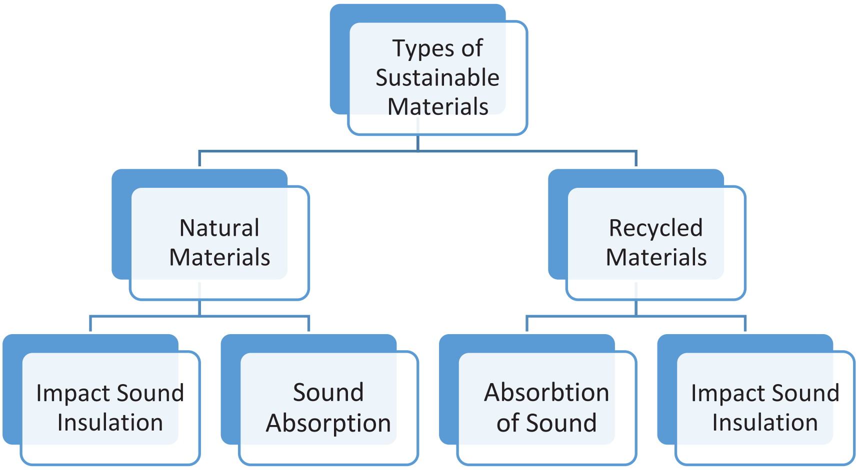

Fig. 2: Types of sustainable materials.

In the above fig. 2 types of sustainable materials is explained as they often function comparably to traditional materials in terms of heat and acoustics. Below is the explanation of each property of natural and recycled materials.

2.2 Recycled Materials

A variety of recycled materials, including plastic, textile agglomerates, metal shavings, and rubber scraps, can be utilized to make acoustic materials. To achieve the necessary properties, it might be helpful to combine a number of recycled materials with different granulometries; in these situations, the right quantity of adhesive or glue must be used.

- **Absorption of Sound**

  The most common recycled substance for improving the acoustic quality in enclosed areas is cellulose, which is mixed with biocides and flame retardants and extracted from old newspapers in Fig. 2. The sound-absorbing qualities of wet cellulose fibers, which are often sprayed directly onto walls or ceilings, are much superior tothose of mineral wool. Textile agglomerates and shavings of metal are two more potential materials [20]. Because of their longevity, rubber crumbs make excellent Acoustic materials with an extensive range of absorption for traffic noise barriers [9].

- **Airborne Sound Insulation**

  Particularly in the United States, dry loose cellulose particles have been widely utilized to fill up the spaces left by roofing and wall construction for acoustical and thermal insulation. It seems to correlate with health concerns, energy and raw material savings, and the use of recycled newspapers. The acoustical qualities are on par with those of conventional ones.

- **Impact Sound Insulation**

  Since tires are no longer allowed in landfills and stockpiles pose a risk of fire and vermin infestation, recycled rubber layers formed of used tire granules are an intriguing substitute for conventional materials in this application. With so many old tires on the market worldwide, there is a need to find new uses for them, and impact sound insulating layers seem like a highly promising option [19]. When it comes to impact sound insulation, recovered carpet wastes are very intriguing materials, particularly if they combine granular and fibrous waste. These underlay materials' acoustic qualities are on par with those of ones that are sold commercially [22], [23].

3 Honeycomb Metamaterials

Excellent mechanical performances are achieved by the hexagonal honeycomb cores that make up the suggested RHA structure. The RHA's ultra-wide-incident angle characteristic (angular stability) was validated by examining the power loss density distributions and the induced electric field. We have shown that the most efficient absorption factors of the proposed RHA are the ohmic losses of films, notably those perpendicular to the direction of applied electric field, by increasing the electrical conductivity, which can be continuously controlled. Moreover, power loss tends to migrate to the lateral sides of films rather of the upper and lower films when the oblique incident angle increases. Because of its entire incident angle absorption, angular stability, and mechanical performance, we think the suggested absorber has a lot of potential for engineering applications.

Fig. 3: Honeycomb metamaterials structure [16].

One of the first ideas for acoustic metamaterials that showed great efficacy in isolating low-frequency sound made use of resonant membranes [19]. With a rigid honeycomb and a flexible outer layer, one such design—referred to as a meta-structure (Fig. 3)—produced a sound reduction index (R) of 45 dB below 0.5 kHz. The design has undergone a number of changes to enhance performance at specific frequency bands. Honeycomb constructions have high strong-to-weight ratios. These structures, whether man-made or natural, minimize the amount of material required to attain the lowest weight and cost.

Beehives made of wax and wasp nests made of paper are examples of natural honeycomb structures. It was most likely the honeybees' hexagonal lattice, an acclaimed ancient construction, that led Euclid to propose the hexagonal shape as the most effective use of building resources and available space.

4 Discussion

Table 2 presents a noise absorption frequency over a range of models based on a numerical forecast of the Honeycomb model's absorption coefficient using comsol multiphysics software. The PC structure's capacity to insulate sound was tested, and the findings were satisfactory in both the low and high frequency ranges. An ascending noise insulation curve that progressively increases from low to high insulation ranges is depicted by the PCs structure findings.

Coefficient Model of Absorption

Using the Comsol Multiphysics tool, the absorption coefficient of the model is estimated, and free and continuous boundaries are established between the solid and air domains. Applying a plane wave emission at the upper border with an incident pressure field $P_{inc}= 1_{Pa}$ on the model surface, the actual backdrop pressure is provided as,

$$P_{inc}= e^{-i\,(K.x)} \quad (1)$$

where x is the distance from the air-porous interface and k is the wave number, and the acoustic-poroelastic coupling condition is applied horizontally. The Johnson-Allard equivalent fluid model is used on the PCs. The model uses five non-acoustical parameters—tortuosity, flow resistivity, porosity thermal characteristics length, and viscous characteristics length—to determine the effective bulk modulus and density of the rigid framed porous material.

Table 2: Comparative analysis between acoustic metamaterials.

Material	Size (mm)	Frequency (Hz)
Waveguide and MPP metamaterials	540	1000
Acoustic metamaterial	500	1170
Helmholtz resonators	620	1360
Resonance	420	600
Coplanar waveguides	170	600
Coiled waveguides	240	1268
Honeycomb corrugated core	600	2000

Table 2 enumerates a few outstanding designs creating metamaterials with a typical characteristics which is the key to implementation. In actuality, acoustic cloaking has a higher chance of success than electromagnetic (EM) cloaking. The rationale is that sub-wavelength scale structure is required in the cloaking material. The acoustic problem is theoretically easier since acoustic wavelengths are often orders of magnitude larger than optical wavelengths, measured in meters vs microns.

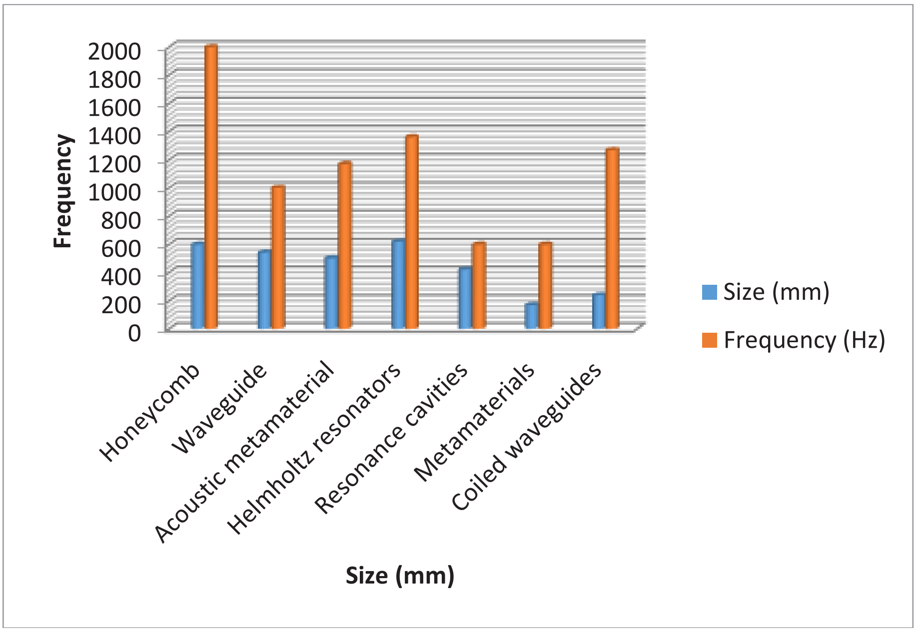

Fig. 4: Graphical analysis of honeycomb with other materials.

It would be fascinating to design and test other materials for the size and frequency characteristics shown in Fig. 4 and compare their strength to that of the conventional honeycomb structure. An interesting possibility of investigation would be to evaluate how well they absorb sound. It's expected that in the near future, a completely new class of acoustic met materials which are more effective and less in size and expand the acoustic properties will be made possible by the growing interest in expanding the range of acoustic metamaterials and the design flexibility provided by the utilization of additive manufacturing (3D printing).

5 Conclusion

One subset of a larger category of composite materials with special qualities that have been intentionally created is called acoustic metamaterials. When creating acoustically sustainable goods, natural or recycled materials might be a good alternative to traditional synthetic materials. Natural materials like flax and recycled cellulose fibers offer an airborne sound insulation that is similar to that of glass wool or rock.

- Many natural materials, such bamboo, kenaf, and coco fibers, are excellent at absorbing sound; cork or recycled rubber layers are good for impact sound absorption. These materials are typically safe for human health, lightweight, and provide good thermal insulation properties.
- Major types of acoustic metamaterials are defined their key application areas are discussed. Additionally, simulation software packages are discussed which can be used for design and numerical simulation of metamaterials.
- The results where honeycomb corrugated core combined with resonance cavities contains size of 600 and the frequency range for it is 2000Hz, which is the highest among all other metamaterials. Life Cycle Assessment methodologies must be used to fully

examine the sustainability of these materials, even if their fabrication frequently has less of an environmental impact than that of traditional materials.

- This study also provides an overview of primary sustainability evaluation approaches.

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