Review Article

A Comprehensive Review on Noise Reducing Materials for Habitable Spaces

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Abstract
Millions of people are subjected to stress, particularly hearing losses due to the adverse impact of noise pollution. Noise mitigation demands inexpensive, efficient and feasible solutions to be developed in habitable spaces including long duration transport systems. The comprehensive review presented here focuses on different noise reducing materials being utilized presently, including recent developmental efforts towards noise mitigation. Sound absorption characterization and associated material parameters are presented initially. The material parameters affecting sound absorption are listed and defined subsequently. A summary about the foaming agents being widely utilized is presented next. The different materials like foams (open and closed cell), metamaterials, sandwiches, and microperforated panels are reviewed in detail before introducing the simulation studies of acoustic wave propagation in cellular structures. The applications are summarized before possible future trends and challenges in developing advanced smart, sustainable noise mitigating material.

Keywords: Noise mitigation, Sound absorption, Foaming agents, Foams, Sandwich composites

1 Introduction

Human society is poised for minimized noise pollutions in habitable spaces. The space/room/enclosure intended for the incidental usage and human habitation by one or more personnel for sleeping, living, eating, studying, and traveling is called habitable spaces, and the sound wave is an integral part of it. Maximum time of the humans is spent inside the built environment or traveling inside an enclosed space e.g., traveling in railway, which generally involves longer travel hours. In recent times, another mode of transport i.e., Caravan tourism has also gained momentum owing to the current pandemic situation of COVID-19 due to the flexibility it provides in travel and stay. The spaces inside such transport facilities are also in need due to consideration of the comfortable habitable space having focus on the proper ventilation, sound and lighting. Getting used to the sound accompanied within these spaces becomes inevitable [1]. The current situation has also taught us the need for comfortable habitable spaces for people to stay healthy during situations such as being in home and institutional isolations. Recently, the Indian Government tackled such an increased demand for private habitable spaces for the COVID patients by making nearly 4000 COVID Care railway coaches with almost 64000 beds ready for use by the different states in the country. All these scenarios need noise mitigations at the highest levels.

The increased noise pollution is due to the exponential growth of industrial developments associated with rapid transportation activities. The well-being of the wildlife and society is substantially hampered by excessive and continual exposure to noise above 65 dB (noise pollution as defined by World Health Organization). The prolonged exposure leads to stress, sleeping disorder, cardiovascular diseases, hearing loss, and less concentrations, in addition to substantially lowered work efficiencies. The most feasible solution for mitigating noise pollution would be the development of efficient sound absorbing or acoustic materials. The acoustic materials are basically designed to improve the quality of the sound and avoid unpleasant repercussions/resonance and echoes within habitable spaces [2].

Rail transportation is the most eco-friendly lifeline of any country, promoting sustainable developments in a given habitable space. Since 2005, globally, transportation through railways has been growing exponentially [3], [4]. Noise pollution is an integral part of this mass transit locomotive system. The crew and the people traveling in such enclosed semi-habitable space are subjected to noise, adversely affecting the health of the travelers. The noise mitigating materials like foams, sandwich composites, metamaterials, and microperforated panels are extensively used in habitable spaces, including interiors of various enclosed environments. This paper deals with a comprehensive review of these materials. For example, sandwich composite panels are used in rails for enhanced sound absorption coefficient (SAC). These sandwiches are utilized in the interior region/separating the exterior and interior as well because of their inherent lightweight and flexibility properties, which use different materials as part of the core and skins. The combination of different cores and skins permits retaining the required stiffness with higher specific mechanical properties. Further, in enclosed spaces, the demand for other materials for interior and exterior will be very well satisfied by such a multi-material sandwich composite exhibiting enhanced sound absorption and thermal insulative characteristics. The combination of the perforated panel, porous material (foam), and honeycomb material systems are also widely explored for noise mitigation in habitable spaces and dealt with in this comprehensive review.

The two most commonly available materials resonate and porous absorption types. The micro-perforated panels (MPPs) fall under the resonator type that can be utilized as a standalone or as the facing materials for porous structures for enhancing lower frequency sound absorptions. These resonator type materials exhibit the effect of sound absorption on the cavity/space between the back (rigid) and sheet/facing resulting in a resonance acoustic absorption mechanism. The vibrational energy of the panel is attenuated because of structural constraints and internal friction and is subsequently converted into heat for dissipation. MPPs are better suited for lower frequencies as these frequencies lead to vibrations [5], [6]. The structural resonance creeps in when the panels' natural frequency matches that of incident sound wave frequency. On the other hand, porous materials have pores interconnected, permitting the acoustic wave to pass through and dissipate the energy due to frictional heating between pores and vibrational air molecules and the transfer of energy across the pore wall and air interface [7]. The pore structure strongly influences the penetration of the sound wave in porous materials. It may penetrate more or less within the material, depending upon the geometry of the pores. Pore geometry can be tuned for effective acoustic wave absorption within the MPP by frequently reflecting the sound wave. A larger pore size yields higher attenuation of sound because of the higher amount of energy transfer into the structure. Though porous materials have relatively simpler processing routes, a wider acoustic range of absorption, and are comparatively inexpensive, they have an inherent mismatch of impedance, resulting in lower absorption at lower frequency ranges (< 800 Hz) [8]–[10]. This paper presents a comprehensive review of noise-reducing materials focusing on acoustic parameters. Further, porous materials are discussed, including commercially available polyurethane (PU), MPPs, and foams. The metamaterials for sound absorbing applications are dealt with briefly as they have great potential in mitigating noise reducing designs through 3D printing. The researchers' findings about the various strategies for acoustic wave mitigations are summarized before concluding remarks about the upcoming challenges in developing sustainable, eco-friendly and smart sound absorbing materials in habitable spaces.

2 Sound Absorption Characterization and Associated Material Parameters

The SAC and STL (sound transmission loss) are the two basic parameters explored in acoustic wave characterization.

2.1 *SAC*

SAC, α can be estimated through impedance tube in accordance with ISO10534 [11], [12] or ASTM E1050-12 [13]. Figure 1 presents the schematics of the experimental set-up for estimating SAC. Samples of disc configuration having 30 and 100 mm are used respectively for higher and lower frequency ranges. SAC is computed as [5], [11] Equation (1),

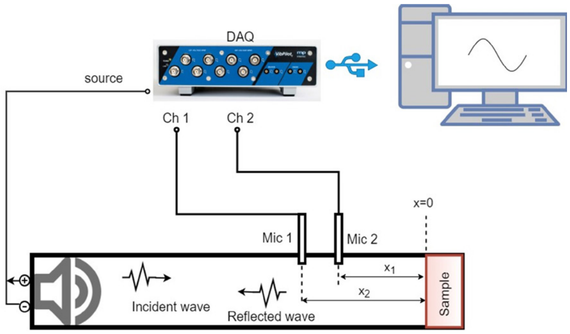

Figure 1: Schematics of SAC measuring set-up [5]. Reproduced from [5] with permission from Elsevier.

$$\alpha = 1 - |R^2| \quad (1)$$

where reflection coefficient is denoted by R which is estimated using [5] Equation (2),

$$R = \frac{e^{-jkS} - H_{12}}{H_{12} - e^{jkS}} \times e^{2jk(l+S)} \quad (2)$$

where l is the min. distance between the sample and the microphone (Figure 1) and the acoustic transfer function is represented by H_{12} which can be estimated by [5] Equation (3),

$$H_{12} = \frac{p_1}{p_2} \quad (3)$$

where, p_1 and p_2 are the sound wave pressures measured from the microphones (Figure 1).

2.2 *Sound Transmission Loss (STL)*

STL is quantified as per the ASTM E 2611-19 [13] using the transfer matrix method. The experimental set-up representation is shown in Figure 2 that uses four microphones placed at X_1, X_2, X_3, and X_4 in an impedance tube. The sample to be tested is placed between the transmission and reflection side. The loudspeaker on the left side (Figure 2) emits the noise. The other end of the impedance tube is fixed with reflective sound absorbing material. At different locations, X_1–X_4, the sound pressures, $p_1 - p_4$ are measured through microphones. STL is Equation (4),

$$STL = 10 \log \frac{1}{|\tau|^2} \quad (4)$$

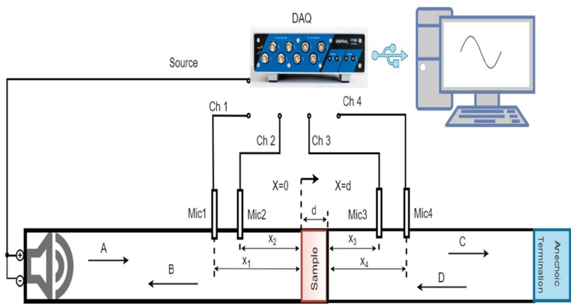

Figure 2: Schematics of STL measuring set-up [5]. Reproduced from [5] with permission from Elsevier.

τ - coefficient of normal incident pressures transmission. STL can be measured also using ISO10534 [11], [12] and ASTM: E1050-12 [13]. These standards outline the procedure for measuring the wave power lost in decibels across the panel (porous type) using Equation (5),

$$STL = 10 \log \frac{I_1}{I_2} \quad (5)$$

where I_1 and I_2 intensities before and after hitting the acoustic wall.

2.3 *Material parameters affecting sound absorption*

2.3.1 Tortuosity

Tortuosity can be estimated using ultrasonic, and resistivity measurements and is given by,

$$\text{Tortuosity} = \frac{L}{C} \quad (6)$$

where L and C are respectively the length of the channel and the distance (straight line) through which sound wave travels. Higher tortuosity might enhance the SAC.

2.3.2 Cell content

Open-cell foam exhibits better SAC than closed cellular structures. Nonetheless, closed cell foam possesses good mechanical properties [14]–[16]. Cell content (CC) influences sound absorption properties and is given by Equation (7),

$$CC = 1 - \frac{V_{air}}{V_{geometric\ volume}} \quad (7)$$

2.3.3 Cell density

The cell morphology is described by the cell density and is a function of foaming time and nucleation rate [17], [18]. Cell density is given by [19] Equation (8),

$$Cell\ density = \left(\frac{n}{A}\right)^{3/2} \times \rho_R \quad (8)$$

n - no. of cells, A - micrograph area and ρ_R (volume expansion ratio) is given by Equation (9),

$$\rho_R = \frac{Density\ of\ the\ unfoamed\ sample}{density\ of\ the\ foamed\ sample} \quad (9)$$

2.3.4 Porosity

The porous materials exhibit higher sound absorption and are typically close to 1 based on the different material parameters as enlisted earlier [20]. The porosity (ϕ) is measured as the ratio of air-filled pore volume (V_{pfa}) of to the total geometric volume (V_{tgv}) and is given by Equation (10),

$$\phi = \frac{V_{pfa}}{V_{tgv}} \quad (10)$$

3 Foaming Agents for Porosity Formations

The superior acoustic response exhibited by open-cell foams made them widely utilized as noise mitigating materials, in addition to their usages in light-weighting applications [21]. The open-cell architecture predominantly depends upon the blowing agents, which promote foaming in the bulk material systems while processing them [22]. These foaming agents are classified as organic and chemical blowing agents. The most commonly used organic foaming agents are azodicarbonamides (170 °C decomposition temperature) that are used in PLAs (polylactic acid), PP, and PBATs [23]–[25]. The open-cell pore structures are created more effectively using inorganic foaming agents. Sodium bicarbonate is one such chemical that decomposes between 140–160 °C [26], [27]. Chemical foaming agents decompose at the thermoplastic processing temperatures of 130–200 °C. On the other hand, inert gas and volatile liquid also produce a blowing effect in bulk materials, known as physical foaming chemicals. Carbon dioxide and nitrogen are most widely used for these purposes as they are cheap, nontoxic, and have minimum water absorption. These physical foaming agents find wide applications in polymers demanding micro-scale cellular architectures [28]. Such a foamed porous structure makes noise to mitigate effectively owing to higher surface areas and larger tortuous paths.

4 Foams

The open-cell foams have interconnected porosity. The PU foam is one of the most widely used open-cell foam presently utilized in seat cushions, furniture upholsters, medical packaging, insulation, and most importantly, shock and sound mitigation applications. Further, these PU foams are extensively used in habitable spaces, including automotive and railway applications for noise mitigation. These lightweight open-cell foams were synthesized in 1954 [29], [30] through RIM (reaction injection molding) [31] and have a wider acoustic wave absorption range, including excellent damping behavior. Nevertheless, they pose serious environmental and disposal related issues releasing poisonous residues [32], [33], complex and expensive recycling approaches in addition to landfill burdens wherein non-decomposable plastic wastes are dumped. In the conventional practices of realizing open or semi-open cell foams for noise mitigation applications basically, two approaches are widely explored.

The addition of fillers includes compliant rubber particles [34], graphene variants [35]–[38], micro and nanoscale particles [39], [40]. These fillers are embedded in combination or individually to enhance sound absorption properties by exploiting the pore structure (porosity, cell shape/density/size) [41]–[43]. Such additional fillers in the matrix mitigate sound waves effectively. They alter cell size, structure, and density and increase the tortuosity due to higher interfacial regions between the polymer matrix and fillers [44]. The synergetic combo effect of multiple fillers vibrations in the matrix results in effective energy dissipation at the interfaces. The crucial aspect is the optimal number of fillers in the matrix without compromising intended properties and the sound noise mitigation. The adverse effect creeps in at higher filler loadings as they directly influence the pore structure detrimentally. The creation of substantially higher interfaces is the key for effective noise pollution reduction. The scale of the fillers plays a vital role and hence nanoscale fillers are found to be the most viable choice for reducing the noise substantially. The surface/interface area increases exponentially as the filler scale reduces from macro-, micro-, to nanoscale. At the filler-polymer interface, sound wave's kinetic energy gets dissipated through frictional heat losses via interface sidings [10], [45]. Nanoscale fillers like CNTs (carbon nanotubes), CNFs (carbon nanofibers), and GNPs (graphene nanoplatelets) are being widely explored to develop nanocomposites with a focus on noise reduction [46], [47]. The higher interfacial regions rendered by these nanoscale fillers hampers the SAC at higher loadings due to agglomeration [43]. Hence, it is very vital to explore the influence of varying filler contents on SAC. The incorporation of CNTs by 1 weight % in PU has enhanced the sound absorption properties by 23% in the 2000–6000 Hz frequency range and is attributed to the interfacial sliding between the nanoscale surface and the polymer chain [48]. In another investigation carried out by Huang *et al.* [49], graphene content of 4 weight % in PU coating has resulted in the maximum SAC. The PU foams varying densities are exploited by embedding GO (graphene oxide) for noise mitigation applications [30]. The tortuosity (Section 2.3.1, Equation (6) plays a crucial role in effective sound absorption. The interconnected porosity can be selectively closed to render a more tortuous path for the acoustic wave to propagate and dissipate the heat more effectively. The addition of GO is quite effective in closing a few of the open-cell based on its addition. The optimized amount of the GO addition results in the more tortuous path leading to enhanced SAC. Further, GO addition in PU foam can be varied to tune the SAC over a particular range of frequency. Graphene enhanced the PU foams SAC by promoting more tortuous paths and smaller cells [50]. Other nanoparticles aiding the SAC enhancement include SiO_2 (silicon dioxide) nanoparticles wherein their morphology, size and content significantly influence the acoustic response. The incorporation of 0.05 weight % of SiO_2 in PU foams has resulted in ~90% increase in SAC as compared to the neat PU foam over 500–1000 Hz frequency range [51]. Higher than 0.05 weight % resulted in cell inhomogeneity. The hollow particles have porosity within and might help in enhancing SAC further with an additional air/crust interface. The incorporation of hollow micro/nanospheres results in closed cell foam, also known as syntactic foams [52]–[54]. The combo effect of closed cell foam within the open-cell foam increases the interfacial area. Silica particles in rigid and hollow foam enhanced SAC. In particular hollow silica particles were found to improve noise mitigation more effectively than their rigid counterparts [55]. The surface modification of the fillers is also observed to enhance SAC owing to the higher interfacial regions, especially at lower frequency levels [56]. Further, a rise in SAC by 100% over 50–6400 Hz frequency range is exhibited by nanoclay incorporation in PU foams [57]. The viscous damping is another route through which noise pollution reduction can be achieved wherein dissipation of sound is realized through rubber particles [58]. The GTR (ground tire rubber) content, treatment, and size have shown the effect on GTR reinforced PU foams [59]. The foams foamability is substantially affected by the GTR treatment. More uniform pore structures are observed with smaller GTR particles. The milled GTR governs the flexibility of the chains at higher filler content leading to higher SAC values. Further, EPDM (ethylene propylene diene monomer) particles promote high cell densities, homogeneous morphology, and formation of small pores resulting in enhanced noise mitigation of PU foam across the frequency of medium range [60].

In addition to modifying the existing foams materials to enhance the SAC by altering the pore morphology (homogeneity, density, size and tortuosity) through reinforcement additions, most recent efforts are directed towards synthesizing cellular material systems with hybrid and hierarchical patterns. These hierarchical structures can be made to respond efficiently to the acoustic sound wave with tunable properties and are realized through 3D printing [61], impregnation [30], electrospinning [62], CVD (chemical vapor deposition) methods [63], and freeze-drying [8]. The GO treated hierarchical PU foam revealed a substantial rise in SAC due to GO sheet vibration, longer tortuous paths, and frictional damping between GO and air [64]. The flexible foams in the wavy pattern made out of graphene exhibited enhanced SAC (350% as compared to neat foam) because of the interactive forces within the multiple GO layers and PU [10].

The GO coated CNT reinforced melamine foams revealed ~100% enhanced SAC at lower frequencies [65]. The same foam made out of melamine exhibited 60% higher SAC across 120–4000 Hz [44]. The GOs presence in these PU foams increases tortuosity leading to higher damping (viscous) and acoustic wave reflections within and across the pores resulting in higher sound energy dissipation. Another class of exciting materials that expands 90° to the load is called auxetic structures. These materials have Poisson's ratio with a negative magnitude, which can be tuned based on the structure and manufactured through settling heat in conventional three-dimensional compressed PU foams [66]–[68]. 3D printing is another most feasible approach, recently, wherein such auxetic structures can be realized efficiently based on the requirements. In addition to these conventional and advanced manufacturing methods, presently focus is on biological routes in achieving auxetic morphology through the metabolic activities of the microorganism [69]. These unique and novel structures are being widely explored in the defense and construction sectors due to their extraordinary fracture resistance and higher energy absorption capabilities. Though these auxetic structures are unique, their SAC is yet to be explored to the full potential as a function of their tunable structural parameter. PU foam having auxetic structure revealed enhanced SAC across 100–1600 Hz range of frequency [70]. These auxetic PU foams are observed to possess substantially higher SACs in 1000–2000 Hz [71], [72]. Further, tunable auxetic PU foams embedded with iron particles rendering the magneto-rheological fluids behavior under the influence of magnetic fields are also synthesized efficiently [71]. The pore structures in the twisted form in the GO dip-coated PU foams exhibited the best SAC due to the combo effect of the wrinkled two-dimensional GO and three-dimensional auxetic geometry [73]. Nonetheless, multifunctional auxetic recoverable PU foams would be an interesting material to explore for noise mitigation capabilities [74]. The PU foams are not eco-friendly as compared to the foams realized through thermoplastics. Thermoplastic foam can be easily recycled and are easy to manufacture using injection molding [75]–[77], compression molding [78], [79], and Additive Manufacturing/3D Printing [14], [15], [52]–[54], [80]–[85]. Mu-Cell® process developed at MIT (1990) is very well known for realizing cellular structures at micron levels (0.1–100 μm) through Injection molding [86].

The closed cell foams are manufactured by embedding the hollow microspheres in the resin [87]–[89]. The noise mitigation is governed by the passage provided by the materials system for the acoustic wave. In closed cell foams, as sound cannot pass through the channels of the pores, the SAC of these syntactic foam is similar to that of the solids [19]. The PP foam manufactured through injection molding has shown 73% cell contents with a 4.6 expansion ratio exhibiting 0.95 SAC [19], [90]. The PEBA thermoplastic elastomer foams synthesized through injection molding showed 39 μm-pores with enhanced SAC across 1000–4000 Hz [91]. PP foams created using Carbon dioxide by incorporating PTFE particles showed enhanced SAC because smaller pores have higher density [92]. Nevertheless, at lower frequencies (< 1000 Hz), SAC is yet to be improved.

5 Metamaterials

Metamaterials comprise the elements of multiple materials arranged in a typical repeating pattern. Most importantly, the scale of these structures is much smaller than the wavelength of the scenario they affect. These metamaterials are the most effective class of materials in manipulating and controlling noise. The periodic/non-periodic structure/elements exhibit negative/zero refractive indices against the conventionally manufactured porosities having blocks of subwavelengths [93]. The sound wave behaviors of these metamaterials can be mechanically tuned to any value (zero/negative preferably) for impedance matching with the associated media to enhance sound absorption. Hence, their sound absorbing characteristics are far superior to the conventional and commercially available materials at even lower frequencies (< 800 Hz) [94]. Types of the sound absorbing Metamaterials are listed in Table 1.

Table 1: Types of the sound absorbing metamaterials

Type	Membrane	Cavity	Gradient
Elements	Prestressed/ pretensioned having weight attachment	MPPs [5], [6] Coiled, Helmholtz oscillator [95]–[100]	Graded (nonuniform) structural design
Frequency range (Hz)	< 150	200–1500 [101], [102]	500–4000 [103]

The cavity and membrane-based metamaterials exhibit sound absorbing performance in a narrower band of a single frequency. The graded absorbers with varying structural designs have extraordinary sound wave absorption and are potential candidate materials to be exploited/tuned in the future. The recent advancements in manufacturing methodologies (additive manufacturing/3D printing) might push the limits of developing novel tunable and multifunctional metamaterials to a much greater height [104]–[106].

6 Sandwich Composites

Sandwich composites comprising of two thin skins on top and bottom of thicker cores are potential materials in many noise mitigation applications. PU foam is a core sandwiched between fabrics placed on top and bottom, also known as skins. Such multi-material systems (skin and core) make the acoustic wave transmitted across different intricate porosities, enhancing sound dissipation through vibration damping, internal friction, and losses via viscous flows. The processing route predominantly governs the SAC in sandwiches adopted [107], constituent elements (skin/core interface, skin and core elements) interactions [107]–[109], and density of the foam core [109]. The sandwich panel's rise in density and thickness respectively decreases and increases the SAC [110]. Using carbon fibers as a fabric in sandwiches' skins with PU cores reveals 0.904 SAC with semi open-pored interconnected structure (50– 250 μm) [107]. Wu *et al.* [107] further explored spacer fabrics in nonwoven LPET sandwiches through three fabrication routes [107]. They reported the best SAC of 0.997 (1000 Hz) for the needle punched sandwich processed through hot pressing due to multi-scale porosity in PU foam, nonwoven, and spacer fabrics. Another sandwich panel with filler hybridization of Kevlar and carbon fiber with PU foams exhibited 0.5 SAC across a frequency range of 1500–2500 Hz [109].

7 Microperforated Panel (MPP)

The panel with perforation has noise mitigation capabilities at lower frequencies. They comprise of perforations at millimeter to sub-millimeter and backing cavities. They are a special class of porous materials having holes in the panel [20]. These panels are eco-friendly, moisture resistant, and most importantly, SAC can be manipulated for a specific frequency by altering MPP parameters [111]. The two researchers, Maa [112], [113] and Kim [114], have extensively worked on predicting MPPs sound absorption response. Maa has proposed simpler mathematical equations, whereas Kim dealt with fluid-structure interaction. This special class of porous materials can have effectively designed tortuosity [115]. The equations pertaining to smaller deviations between nonlinear and linear sound waves are also proposed for MPPs. The mechanism of noise mitigation in MPP is governed by the phenomena of resonance and the design/pattern of holes. The perforations in the PP panel increased the frequency range of sound wave mitigation without much improvement in STL [90]. The influence of perforation depth and rate in PU panel on SAC is estimated by Lin *et al.* [116] and noted the enhanced noise mitigation for a medium-high range of frequencies (125–4000 Hz). The 50 and 75% perforation depths at 3% perforation rates resulted in a substantial rise in SAC. Nonetheless, as the MPP parameters cannot be changed dynamically in a given panel, they have a narrow range of operative frequencies. Different strategies can be adopted to resolve these issues. Introducing corrugation in the panel is one option wherein depth and pitch can be designed efficiently for effective SAC. The comparative investigations on flat and corrugated (sinusoidal) MPP for the same material revealed the significance of corrugation depth than the pitch [117]. Such a corrugated designed panel can be utilized in buildings for effective noise mitigations. Additional honeycomb structured backing and branching of air cavities can also significantly enhance the MPPs acoustic wave mitigations [118].

The SAC can be tuned by smart designs, e.g. introducing adjustable perforative elements in honeycomb MPPs. The single panels SAC at a lower frequency can be further enhanced by having series [119], arrays of MPPs [120], and parallel arrangement [111]. The highly porous structure with micro-scale pores in the form of micro-capillary plates exhibited a wider band of lower frequencies. SAC of MPP with different cross-sectional perforation holes revealed enhanced performance compared to the uniformly perforated panel for a particular frequency [5]. Further, the influence of graded and uniform spherical perforations on SAC showed that gradation enhanced SAC at lower frequencies [6]. A graded perforation is a promising approach for effective noise mitigations at lower frequencies.

8 Simulation Studies

In the recent past, substantial progress has been made towards porous materials modeling using simple, sophisticated, and finite element methods [121]. Commercially available packages like ANSYS, COMSOL Multiphysics, etc., are widely explored for predicting the acoustic performance of materials. Recently Sailesh *et al.* [5] presented a procedure for SAC and STL estimations using commercially available COMSOL Multiphysics 5.4 software. They utilized an acoustic module that is suited for plane wave conditions. The fluid-structure interactions are ignored, substantially reducing the time of computations. The MPPs model only takes into account the volume of air present in the system. They have considered 3 domains (incident pressure field, perfectly matched layer, and MPP) in the CAD model (three-dimensional) for sound absorption simulations. For STL simulation, PML and transmitted pressure fields are considered. PML is placed at the pressure field's end as it absorbs the energy without reflecting and activates non-reflecting regimes. The sound hard boundary condition with 1 Pa pressure was applied. PML was mapped with Hexahedron elements having user controlled meshing. The remaining domain used Tetrahedron elements having meshed with free type. The mesh size depends on the six-element requirements for each wavelength of the maximum frequencies [5]. In the case of MPPs simulation, the very narrow acoustic zone in the perforated hole is modeled through a thermos-viscous module to consider thermal and viscous losses. As an outcome of the simulation post-processing, the reflection coefficient is estimated by Equations (11) and (12),

$$Reflection\,coefficient = \frac{Reflected\ pressure}{Incident\ pressure} \tag{11}$$

STL is estimated by,

$$STL = 10\log\left(\frac{W_{in}}{W_{out}}\right) \tag{12}$$

where, W_{in} and W_{out} are the input and output sound powers.

The initial work carried out by Biot [122], [123] and Zwikker and Kosten [124] is the fundamental building block for all the theoretical equations for sound propagation in pore structured cellular materials. Though there are many predictive models, including empirical equations [124]–[128], semi-empirical [129]–[131], and FEM models [5], [6], [132], predicting acoustic response in the human hearing range using theoretical foundations is yet to be proposed.

9 Applications

The noise mitigating material finds extensive and numerous applications across many sectors. Typically, these sound absorbing materials are widely utilized in habitable spaces, including railway interiors, automotive, marine, space, infrastructure, and building regimes. The habitable interior spaces like cinema theatres, auditoriums, schools, office spaces, studios (recording) extensively utilize MPPs and cellular structures foams. These foams and panels are attached to the roofs, ceiling, walls, doors, and floors for effective noise mitigations. In addition to manipulating the compositions of these panels/cellular structures, shapes (pyramid, egg crate, wedge-type etc.) are also designed smartly for enhancing SAC by increasing the surface area. The noise mitigations are also efficiently achieved by corrugated MPP arrays/ backing layers, as mentioned earlier [133]. The paddings made of nonwoven type fabrics are used in floor, and door panels of wagons/vehicles to improve sound wave performance. Thermoplastic open or semi-open cellular structures are utilized in habitable spaces for effective noise mitigations.

10 Future Trend and Challenges

The sound absorbing materials commercially available have substantial carbon footprints and are neither eco-friendly nor sustainable. The recyclability potential needs to be explored in accordance with the circular economy for the material being developed for noise mitigation. More focus topics should be on the development of sustainable and biodegradable sound absorbers. The effective and efficient usage of sustainable materials such as, flax, coconut and cellulose fibers, sheep wool in combination with different materials are in need to be explored for noise mitigation. Further, sustainable processing routes should be explored in addition to exploiting recycled materials for enhancing SAC. The scalability issues need to be addressed critically and effectively. The significant challenge lies in the development of an intelligent sound absorber, which can change the geometrical and material parameters intrinsically based on the external stimulus.

11 Conclusions

The presented comprehensive review deals with noise reducing materials for habitable spaces, including interior, rail wagons, automotive, and transportation sectors with elaborate discussions on different noise mitigation strategies and mechanisms for enhanced SAC. The SAC and STL are listed with their estimation formulas in addition to the associated material parameters including Tortuosity, Cell content, Cell density and Porosity. Further, different foaming agents are also mentioned, creating open cellular architecture in the bulk material for effective and efficient noise mitigations. These foaming agents are instrumental in developing porous structures with different porosity levels, pore sizes and shapes. Depending on the noise mitigation mechanism, strategies and feasible solutions in metamaterials, foams, sandwich composites and MPPs are elaborately discussed, and the observations are summarized. The usage of multifunctional materials having a combinatorial effect can effectively enhance SAC over a broader frequency range. The summarized strategies with conclusive remarks on future trends and challenges as presented in this comprehensive review might benefit through the development of value-added smartly designed the next generation intelligent sound absorbers for habitable spaces.

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