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Advances in 3D-Printed Polymeric Materials for Sustainable Thermal and Acoustic Insulation

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ABSTRACT

Additive manufacturing (AM) creates a way of producing engineered polymeric systems with programmable porosity, shapes, and multi-functionality that is innovative for producing sustainable thermal and acoustic insulation solutions. This document reviews new advances in engineering 3-Dimensions printed porous polymers and how the structure of these materials influences their properties. The research focuses on important design aspects of these materials, including: infill density, unit-cell topology, pore size, and triply periodic minimal surfaces (TPMS) and includes a detailed review of the relationship of design aspects and three key properties (density, thermal conductivity, and sound absorption). Examples of engineered and environmentally friendly systems, such as Polylactic Acid (PLA) lattices, polymer/aerogel composites, bio-fiber composites, and recycled nonwoven composites, offer pathways to low-impact, high-performance insulation. Although standardization issues, durability under in-service conditions, and challenges when scaling production remain significant hurdles for large scale production, opportunities future technology developments include multi-material printing, hierarchical architecture based on triply periodic minimal surfaces (TPMS), smart/4-Dimensions printed insulators (insulators that are adaptive based on environmental conditions), and the creation of tunable, lightweight and resilient insulators are highlighted. The document concludes with a review of the identified gaps in research and suggested directions for future development of large-scale sustainable thermal and acoustic solutions through integration of material chemistry, additive manufacturing (AM) process control and physics-based modeling.

1. INTRODUCTION

The implementation of advanced technologies such as additive manufacturing (AM) and 3-Dimensions printing has changed the way in which architects, engineers, and designers are able to develop and manufacture composite polymeric materials. By using layer-by-layer additive processes, composite polymeric materials can now be manufactured using complex porous geosystems with improved mechanical and thermal properties, controlled porosity, controlled connectivity, and geometrical customization for multiple performance applications. Due to the ability to create thermally insulative and sound-damping compact structures for the construction industry, manufacturers and researchers are recognizing the potential for the future of 3-D printed porous polymers [1].

The ability to digitally create and code the innermost structures of the architectures—changing parameters like infill density, unit-cell topology, pore size, and orientation—gives polymeric materials an almost unlimited control over their thermophysical and acoustic behaviors. Such tunability makes it possible to establish a direct link between the structural design and transport phenomena, thus allowing the optimization of materials for certain targeted functionalities.

Extrusion-based processes which include fused filament fabrication (FFF) and fused deposition modeling (FDM) are the major ones among various AM techniques by which polymer lattices can be produced. These processes are preferred due to their accessibility and cost-efficiency. Besides that, other techniques—stereolithography (SLA/DLP), selective laser sintering (SLS), and direct ink writing (DIW)—can achieve higher spatial resolution and can work with more materials. However, these methods still face some challenges, such as a small number of high-performance polymers that can be printed, anisotropic thermal behavior, and low conductivity that together limit large-scale use. In addition, the defects caused by printing and anisotropy make it difficult to predict and standardize properties, thus industrial qualification becomes more complicated [2].

A recent study [3] has shown that 3D-printed polymeric materials have the capacity to function as an efficient thermal management and acoustic soundproofing material. They have the ability to provide thermal insulation at thermal conductivities from 0.03–0.08 $W \cdot m^{-1} \cdot K^{-1}$, comparable to traditional insulation panels, which indicates that 3D printed composite materials can be a more environmentally friendly option for use in the construction field than traditional insulation options [4]. The porosity of the materials allows for air-filled voids that restrict conductive heating from reaching the outside through the use of conduction and, therefore, conductively transfers thermal energy from one area to another. The thermal conductivity or thermal transfer of these materials will depend on porosity, pore structure, and interconnectivity. For instance, Polylactic Acid (PLA) is a biodegradable material with tunable thermal conductivity depending on changes in the infill density and pore structure [3]. The resulting microstructure (and, therefore, the overall thermal stability) is determined by both the polymer chemistry as well as the respective printing conditions and any post-manufacturing processing conditions [4].

In terms of acoustics, porous polymers can absorb sound energy well if there is insufficient sound energy; this is accomplished by dissipating the sound energy through viscous friction and thermal interaction of the air inside the pores. Microstructural attributes, including the size, shape and connection of the pores, influence the amount of sound energy that will be absorbed. Previous research showed that STL and normal-incidence absorption coefficients for materials printed using 3D printers such as ABS and PLA are comparable to those of other types of porous foams [4, 5]. It has also been demonstrated that architected structures in the design of 3D-printed parts, including lattice, gyroid, and cellular configurations, increase the sound absorption efficiency in broad frequency ranges by specifically targeting narrow frequency ranges [6].

The thermal-acoustic interaction in 3D printed polymeric porous structures is highly complex because of the multitude of factors that influence this interaction (e.g., build parameters—such as layer height and infill pattern—manufacturer specifications, etc.), the type of material used, and the way in which the polymer is created. The understanding of such coupled phenomena is needed to enable the functional design of materials that will be able to act as both thermal insulators and acoustic absorbers [7].

Figure 1 demonstrates (conceptually) the interconnectivity between additive manufacturing build parameters, a material's porous architecture, and the product output's capabilities. Also shown is how the input data (material type and processing method) is transformed into one or more morphological properties (e.g., porosity, geometry), from which the thermal, acoustic, and mechanical property attributes are generated, leading to the available application domains for a 3D printed polymer in any one of the following categories of applications: building insulation, vibration dampening, and lightweight structural systems [8, 9]. Hence, this model represents the journey of optimizing 3D printed polymers that have been developed for a specific Engineering purpose.

As a continuation of the above, this paper reviews the thermal-acoustic properties of 3D printed polymeric porous structures in order to provide a comprehensive connection between the types of designs that exist (theoretical) and the actual ways in which these polymeric porous materials perform functionally. In examining these two extreme design types, it incorporates both synthetic and green types of polymers, addresses the evolving challenges associated with standardization and durability, as well, as furthermore, points out the upcoming research orientations for the scalable and sustainable implementation of energy-efficient built environments.

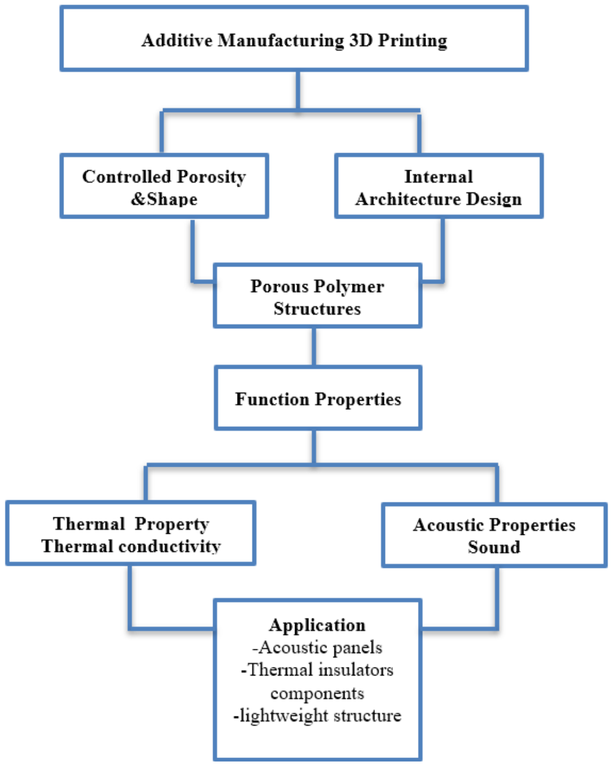

Figure 1. Relationship between 3D Printing, porous polymer structures, and their functional properties and applications [8, 9]

2. THERMAL PROPERTIES OF 3D-PRINTED POROUS POLYMERS

The way that three-dimensional printed porous polymers behave thermally depends mainly on the way that those materials were constructed, which is fully customizable during the additive manufacturing process. The primary structural features of these materials (including infill density, pore shape, unit-cell size and porosity, and connectivity) have a significant effect on their effective thermal conductivity ($k_e$ff) and overall thermal transfer processes. The ability to create any possible geometrical configuration through additive manufacturing makes it possible to manipulate the structural parameters systematically and to adjust polymeric structures to provide a combination of effective thermal insulation, lightweight construction, and multi-functionality. Therefore, the interaction between geometrical shape and heat flow is now one of the major areas being researched to develop future architected polymer systems for use in sophisticated thermal management applications [10].

2.1 Effect of infill density

Infill density has a major impact on the heat transfer properties of 3D-printed porous polymers because it specifies the amount of solid material in the printed structure. This factor controls the number of heat-conducting polymer chains relative to the isolated air pockets, thus calculating the effective thermal conductivity ($k_e$ff) and the total insulation capacity of the material. Physical experiments have shown that polymeric lattices made by additive manufacturing can have very low thermal conductivities, generally between 0.03 and 0.09 W m^{-1} K^{-1}, which is close to the performance of standard insulating materials like glass wool (0.02-0.04 W m^{-1} K^{-1}) [11].

By means of different AM processes—such as fused deposition modeling (FDM), stereolithography (SLA), selective laser sintering (SLS), and direct ink writing (DIW)—thermally functional structures with controlled porosity and customized heat-transfer properties have been produced, which are also light in weight [12].

Multiple research studies [7, 8, 11] have demonstrated that as the amount of infill density is decreased (thus increasing porosity) when 3D printing polymers, there is a corresponding decrease in effective thermal conductivity. The inclusion of air instead of solids for providing heat-transfer paths creates an increasing discontinuity within the conductive network; therefore, an increase in thermal resistance occurs. Tychanicz-Kwiecień et al. [7] noted that with a decrease in infill density the $k$eff values are significantly decreased for PLA, Polyethylene Terephthalate Glycol-modified (PET-G) and Acrylonitrile Butadiene Styrene (ABS), while Krapež Tomec et al. [8] showed a similar decline in conductivity, diffusivity, and effusivity when observed with a decrease in infill density for wood–PLA composite materials, and Islam et al. [11] indicated that highly porous PLA lattice structures can achieve extremely low conductivity values in comparison to traditional forms of insulation materials.

2.2 Effect of infill pattern and geometry

Researchers have demonstrated that the infill type used to construct an additively manufactured polymeric structure is critical in determining how that structure responds thermally and mechanically. The internal structure of a polymeric part (the infill pattern) establishes how heat is conducted, how stress is distributed through the material and how energy concurrently dissipates through the material. Lopes et al. [9] comprehensively studied twelve different infill structures made from PET-G materials and found that just by selecting an infill type it can increase/decrease thermal conductivity by up to 70% and increase/decrease the mechanical performance of a part (when compared to an added equivalent structure): over 300%. Additionally, it has been established that the infill type selected has a significant effect on a material's behavior and performance.

Honeycomb type infill structures have consistently produced the best thermomechanical performance when compared to other infill types due to their high stiffness to weight ratio and efficient load transfer mechanisms between strut junctions. Eryıldız [13] found that honeycomb-infused PLA materials displayed the greatest tensile strength (while using a linear testing method) at approximately 29.43 MPa. This is attributed to improved junction integrity and decreased local stress concentrations as compared to other infill types. Conversely, other patterns, specifically patterned infills that present large air gaps (i.e., space-filling infill or loosely packed infill), do not produce as consistent a mechanical stability or thermal conduction capability due to the use of discontinuous heat-transfer paths [14].

At the architectural scale, the shape of the cavity is the major factor that determines the insulation performance. de Rubeis et al. [10], by means of a hot-box thermal apparatus, compared PLA panels with multi-row, square, and honeycomb cavities and demonstrated that the honeycomb configuration resulted in the lowest overall heat-transfer coefficient ($U = 1.22 \pm 0.04$ $W \cdot m^{-2} \cdot K^{-1}$). The reason for this improvement was the increased tortuosity of the internal channels, which effectively elongates the conductive path length and inhibits heat flow without a substantial increase in mass. In the same way, Lopes et al. [9] found that by changing the rib continuity, orientation, and cell topology from cubic to grid and honeycomb layouts there were significant differences in effective thermal conductivity ($k_e$ff) and thus geometric anisotropy was identified as a key factor in the regulation of thermal transport [15].

All this collective evidence demonstrates that geometrical complexity can improve the thermal inefficiency associated with thermal insulating/energy-transfer materials, by creating longer and more coiled thermal pathway routes, thereby reducing the thermal conductivity of those materials. Additionally, complementary research completed by Islam et al. [11] shows that the geometry of a material's pores exemplifies an additional function of hollow materials; for example, at the same level of porosity, cubic and irregular pore networks exhibit different heat-transfer/energy-transfer behaviors. Therefore, creating an optimal infill geometry of the printed polymeric system is critical to achieving higher mechanical strength and improved thermal insulation performance.

2.3 Triply periodic minimal surfaces (TPMS) and gyroid architectures

In particular, gyroid structures—have been identified as highly viable architectures for next-generation thermal insulation systems due to their topological and structural characteristics of a kind. These structures are non-self-overlapping, smoothly curved surfaces that by default extend the heat conduction channels and at the same time maintain the mechanical properties of the material, thus allowing an ideal equilibrium to be reached between the mechanical strength and thermal insulation. The periodicity and smooth curvature of TPMS structures naturally eliminate the concentrated stresses at a local level and form tortuous ways that effectively hinder conductive heat transfer.

Anwajler et al. [12] produced photocurable resin (DLP)-printed gyroid structures that show thermal conductivity varying from 0.023 to 0.039 $W \cdot m^{-1} \cdot K^{-1}$, which are at least as good as, or even better than, those of typical polymeric foams. The same study carried out energy modeling simulations that showed the use of gyroid-based panels in building envelopes could bring the annual heating energy demand down by more than 15 %, thus confirming their real potential in energy-efficient construction. The results speak to the capability of structures based on TPMS to be the source of lightweight, multifunctional insulation materials that are structurally efficient and have good thermal performance.
Together, the findings of the studies noted above support the hypothesis that commercial products will benefit from all of the above advantages, due to the ability of these materials to be optimized for multiple applications and thus lead to higher performance (thermal and acoustic) than other alternatives. As indicated by Islam et al. [11], the thermal conductivity of 3D-printed PLA gyroids is very low (as low as 0.037 $W \cdot m^{-2} \cdot K^{-1}$), and they can achieve an STL value as high as 48.27 dB, depending on the density and porosity of the print.

The ability of AM to enable the precise control of these microstructural variables through the versatility of design, mass customization, and process-driven multifunctionality elevates the significance of TPMS-structured materials in the production of the next generation of thermally and acoustically efficient materials [16]. Together with results from life cycle cost analysis (LCCA), TPMS-based insulation configurations can yield a substantial energy savings (between 45-67% energy savings) with a return on investment of 8.5 to 14.8 years, demonstrating that both the technical and economic feasibility of TPMS insulation systems [17] is demonstrated. Ultimately, the combination of gyroid and TPMS geometries provides a basis for the development of sustainable, architected polymers for multifunctional energy-efficient uses.

2.4 Influence of unit-cell size and convection suppression

Pore size is a decisive factor which determines the location of the first cells in a porous material where natural convection appears. Alqahtani et al. [18] pointed out that polymer lattice structures with hydraulic diameters less than about 8 mm exhibit pure conduction heat transfer only. Their research also revealed that there was no negative impact on the thermal performance when scaling unit cells to commercial sizes (1 m²), which is an important finding for real-life applications. In a similar manner, Monkova et al. [19] showed that convective heat transport in closed-cell foams is negligible if the Average Pore Size (APS) is Smaller than approximately Six Millimeters (6 mm) versus larger cells (EPS = 6 mm) in size, with the proportion of Heat Transfer through Convection being 20 Percent (20%) for cells >6 mm APS.

The size of cell openings (hydraulic diameter) is the factor that determines when the heat transfer process changes from conduction–dominated to convection-influence [13]. A smaller cell size leads to the elimination of natural convection, so that the conduction-dominated transfer is observed. On the other hand, larger cells may lower the thermal resistance (leading to higher U-values), while smaller cells increase the number of serial interfaces, thus limiting heat transfer [20, 21]. Therefore, the choice of geometry (both shape and size) is equally important as density in the thermal design of 3D-printed insulators.

2.5 Theoretical models to explain the effect of shape

Theoretical models provide workable ways to explain experimental results and predict a system's behavior. A simple model, such as the Maxwell-Eucken model anticipates an almost linear drop of the effective thermal conductivity (k_{eff}) with growing porosity. In reality, architected structures like honeycombs and gyroids can be considered as heterogeneous composites with orientation-dependent properties, which account for the need of advanced modeling methods. To illustrate this, Hrițuc et al. [22] developed an empirical mathematical power function model for 3D-printed PLA panels, showing that sound volume is the factor that influences the acoustic pressure level the most. The same authors, in a parallel study, applied Taguchi L18 factorial experiments to demonstrate that sound frequency has the greatest influence and that PLA panels can reduce sound pressure levels by about 45% [22].

Islam et al. [11] backed up these theoretical methods by thorough experiments in which they obtained thermal conductivity values as low as 0.037 (W/m·K). Monkova et al. [23] went on to say that theoretical models and molecular dynamics simulations offer micro- and macro-level bases, which, when combined with AM, can both confirm theoretical correctness and open up new practical applications.

More sophisticated effective medium theories (E-M-T) include shape factors to better depict the non-spherical or rib-like pores. Nonetheless, contradictions are often encountered among experimental measurements as well as theoretical calculations because of pore interconnectivity, anisotropy arising from the process, and interfacial resistances that are 3D printing process intrinsic. Sophisticated models are necessary to unravel these complexities. For example, a percolation model is able to factor in the tortuosity and connectivity of the polymer network [24], thus producing results that are in a much closer agreement with the experimental data, particularly when the polymer network is near discontinuity.

The theoretical Maxwell-Eucken and Johnson-Champoux-Allard (JCA) models are useful ways to predict how porous materials behave thermally and acoustically. However, currently we have limited ability to apply the theory of each of these models analytically. Therefore, we can perform a simple numerical comparison of the predictions of the theory with actual experimental data. For instance, the theoretical Maxwell-Eucken prediction for PLA (polylactic acid) at 50% porosity would be $k = 0.042$ (W/m·K) whereas experimentally determined $k \approx 0.048$ (W/m·K) for FDM (fused deposition modeling) printed PLA samples of the same density. The 12-15% difference between the two numbers relates to some of the interfacial defects that occur in 3D-printed parts and to print anisotropy and so indicates that model calibration is necessary in order to use these models effectively in practice.

3. ACOUSTIC CHARACTERISTICS OF 3D-PRINTED POROUS POLYMERS

Similar to the thermal properties, vary greatly with their internal structure. Adjusting parameters such as infill density, pattern, and unit-cell geometry, one can create materials with given sound absorption and transmission loss properties.

3.1 The impact of infill density on acoustic performance

Research on 3d printed porous polymers showed that infill density has a major impact on acoustical performance. Research on PLA panels with different structural configurations by Pop et al. [24] revealed that a structure with a core infill and a 1.6 mm shell resulted in the best sound absorption coefficient (α) of 0.99 at 65% infill density. While a core-infill-only structure was better for sound transmission loss (STL) of 53.3 dB) at 60% infill. This explains that different internal structures are most efficient for absorption or transmission loss, respectively.

Similarly, Koç et al. [25] studied the ABS as well as PLA samples having 10–50% infill ratios. They found that ABS with 50% infill caused the highest sound absorption at 2500–3500 (Hz), whereas PLA with 30% infill gave the maximum transmission loss values. The infill density has the greatest impact on the 3D-printed PLA acoustic panels. Zaharia et al.

[17] experimented with five different infill densities (20–100%) in biodegradable PLA panels and concluded that reducing the infill to 40% greatly improved the absorption coefficient (α ≈ 0.93 at 2500 Hz) compared to the denser ones. This behavior can be observed very well, where absorption curves for different densities are plotted. Mid-range infill densities (40–65%) can get the best absorption (α ≈ 0.93) and maintain the stiffness at the same time. On the other hand, very low infill (< 20%) diminishes sound absorption at low frequencies.

Research conducted in recent years has revealed that porosity profiles by grade structures can outperform the standard configuration (uniform) under lower frequency conditions. There are two types of structures that were noted during this study, the first being that the lower-density infills benefit absorption at higher frequencies, while the higher-density infills are more effective on lower-frequency applications. This discovery could provide opportunities for the design of broadband absorbent materials using variable porosity profiles over the entire surface area of the absorbent [26, 27].

3.2 The impact of infill pattern and geometry

Studies reveal that 3D printing parameters have a major impact on the internal geometry, which in turn controls acoustic scattering properties and viscous losses. Naify and Cushing [28] invented homogenization methods to estimate directional sound speeds in FDM-printed PLA with different infill patterns, thereby creating a systematic way of linking infill design parameters with dynamic properties.

Monkova et al. [19] introduced four open-porous PLA structures and found that the triangular as well as circular infill geometries lowered sound reflection by as much as 40% in comparison with solid references. Zaharia et al. [17] found that open-lattice meshes printed with a bigger 0.8 mm nozzle resulted in better mid-frequency absorption.

In addition, the results indicate that geometric tortuosity provides a benefit comparable to that provided by density; in particular, triangular and open gyroid lattices provide a greater level of benefit than regular rectangular and rectilinear lattice patterns. Koç et al. [25] further investigates sound absorption and transmission properties of ABS and PLA materials using square and hexagonal infill patterns and found that the 50% square infill of ABS produced the highest levels of sound absorption at frequencies between 2500–3500 Hz, whereas the 30% square infill of PLA produced the highest levels of sound transmission loss. Sharma et al. [29] also investigated sound absorption and transmission properties of both stereo and FDM printed porous absorber structures, demonstrating that controlling the cellular microstructural architecture (e.g., porosity, surface topology, and gradients) allows for very specific acoustic properties in 3D printed structures.

3.3 Triply periodic minimal surfaces (TPMS) and gyroid structures

TPMS architectures have become the main sound absorption means in a very effective way by their geometrical characteristics and the controlled porosity. The labyrinthine non-intersecting paths of TPMS structures are very efficient in acoustic energy dissipation. The latest study pointed out that TPMS network structures that are fabricated via AM have a very strong capability for sound absorption in different frequency ranges [30-32]. Out of different TPMS topologies, Diamond surfaces exhibited very good sound absorption behavior in a wide spectral region [33] and when Gyroid lattices were used the highest sound absorption coefficients in the range of 0.945 could be attained if all the parameters were optimally chosen [34].

Godakawela et al. [21] examined sound energy absorption behavior of single and multilayer gyroid TPMS structures and found time and time again the coefficients went beyond 0.85 over a large range of frequencies (1000–4000 Hz). In the same manner, the review done by Hrițuc et al. [22] showed the gyroid-based 3D lattices achieve multi-functionality by which they structurally stiffen and simultaneously are highly sound absorbent. The main point of the matter is that TPMS shaped geometries provide lightweight broadband absorption which is on a level with that of heavy fibrous absorbers and thus foams can be used for sound absorption in this range [35-39].

The latest research work has identified such additively manufactured acoustic metamaterials as being in different categories, such as perforated, slotted, cellular, and hybrid, with each having different mechanisms of absorption.

3.4 Influence of unit-cell size on acoustic absorption

Pore dimensions and unit cell dimensions are the most important determinators of the primary acoustic mechanism that will absorb energy, i.e., viscous dissipation or resonance phenomena. Many studies have used stereolithography to manufacture TPMS-based structures and found that structures with small unit-cell dimensions exhibited high acoustic absorption coefficients. Additionally, they produced open porous ABS/PLA panels with incremental pore sizes and verified that < 5 mm pores are efficiently absorbed at high frequencies, while large pore sizes (> 10 mm) allow resonance phenomena to occur and result in reduced low frequency absorption coefficient values [40, 41].

Akhouri et al. [42] have similarly shown that for cell-based metamaterials of DENORMS (Designs for Noise Reducing Materials and Structures), an increased cell count (thus smaller cells for a given volume) changes the absorption response to lower frequencies. The mentioned research works suggest that the size of cells should be of a close association with the target frequency band, with smaller pores generally being more advantageous for high frequencies and intermediate sizes providing more balanced, broadband absorption. Correspondingly, PLA honeycomb structures with hexagonal cells, disclosing that absorption peaks close to α = 1.0 could be attained by the combination of smaller cells with added an absorptive filler [43-47].

3.5 Theoretical models explaining acoustic behavior

Theoretical models enable one to foresee changes in absorption acoustics based on infill density and geometry. The Johnson-Champoux-Allard (JCA) model is a typical representative that sets the rules for estimating acoustic characteristics of porous materials. Johnston and Sharma [48] used the JCA model on fibrous 3D-printed absorbers, and the result showed that predicted and measured absorption curves matched closely. Delany–Bazley, a simple model, on the other hand, was not able to detect changes at low frequencies in complex geometries. Razi et al. [46] have recently moved their modeling work further by TPMS lattices and proving that adding tortuosity factors leads to predictions that are as close as the experimental absorption peaks. Nevertheless, one of the major problems is that defects in manufacturing due to AM, which are at the same time the root of the problem, are usually very complicated to take into account in traditional numerical models; thus, corrected parametric models are needed for accurate predictions. Attempting to solve this problem by linking microscopic geometric quantities to Biot parameters [45] or utilizing sophisticated image processing for direct pore network characterization [47] are some of the ways that have been considered. These works, on the whole, point out that JCA-type models being a link between structure and performance, are still not enough, and there is an urgent demand for new hybrid models that are capable of confronting manufacturing imperfections and can integrate thermal and acoustic transport in architected polymers.

4. MATERIALS LANDSCAPE FOR DUAL THERMAL–ACOUSTIC INSULATION

Researchers have closely looked into the dual thermal and acoustic performance of polymeric materials in various systems, from typical PLA panels to high-tech aerogels and eco-friendly composites. The aim is to pinpoint materials that present a synergistic combination of properties for multifunctional applications.

Engineered Polymers: Islam et al. [11] carried out the investigation of 3D-printed PLA and documented thermal conductivity as low as 0.037 (W/m·K) along with sound transmission loss (STL) values of ~48 dB at 1600 (Hz). Their data indicate that infill densities of the medium range (40-60%) yield the most advantageous compromise between heat resistance and broadband sound absorption.

Advanced Aerogel Systems: As a result of these breakthroughs, advanced aerogel systems have evidenced excellent multifunctionality beyond the board. To illustrate, polyimide aerogels, also SiO_2-reinforced hybrids [49, 50], have been able to achieve ultra-low thermal conductivities (< 0.025 W/m·K), very high absorption coefficients (up to 0.9), and STL values over 50 dB.

Bio-Composites: One of the most promising variants of composite materials is those made from natural fibers and agro-industrial residues. The use of bio-fillers in polymer matrices is the fundamental approach in the creation of environmentally friendly composites with given characteristics. Pop et al. [30] experimented on the biocomposites which are made from natural fibers and measured k ≈ 0.045 (W/m·K) alongside absorption coefficients higher than 0.7 at the middle-frequency range. In the same manner, Segura et al. [31] and Ali et al. [32] utilized the waste of fruits, tea bags, as well as date palm fibers to produce the boards with k ≈ 0.036–0.04 (W/m·K) and α > 0.8 at 2000–4000 (Hz) intervals. These outcomes attest that plant residues can be converted into efficient thermal along with acoustic insulators, thus, achieving the goal of combining eco-friendliness and technical performance.

Nonwoven Polymer Fabrics: Nonwoven materials have been the subject of numerous studies to find cheap insulation alternatives. Usta et al. [33] observed that the mixture of poplar/PET can deliver an R-value ≈ 0.12 (m^2·K /W) alongside α up to 0.78 at 6300 (Hz). Katsura et al. [34] improved the nonwoven fabric by the addition of aerogel granules and thus decreased the k value to ~0.03 (W/m·K) and increased α to 0.85. Karimi et al. [35] investigated polypropylene nonwoven mats and disclosed that k was close to 0.046 (W/m·K) with the acoustic absorption level around 42 (dB). The mentioned experiments indicate that the fiber morphology and aerogel reinforcement can bring nonwoven structures at the same level as multifunctional systems.

Recycled and Reused Materials: Consistent with the principles of the circular economy, tests have been conducted on reused and recycled materials to see if they can be used as dual insulation. Neri [36] fabricated the panels from waste polyester and felt, and obtained k ≈ 0.05 (W/m.K) and STL ~45 (dB). Although their performance is lower than that of the engineered PLA or aerogels, the results show that recycling strategies can provide good insulation while being sustainable.

The polymeric materials spectrum of the literature is the basis for the materials that can be used as insulation. These materials can be engineered (PLA, aerogels), eco-sourced (bio-composites, agro-waste), or recycled (nonwovens, polyester), and they can be gradually adapted to serve the multifunctional insulation purpose [49]. Biodegradable polymers such as PLA, polyhydroxyalkanoates (PHA), and polybutylene succinate (PBS), which are mostly processed through FDM, are at the core of this green production turn, however, there still exist some problems of mechanical performance and biodegradability that need to be solved. The factors that determine the interaction between thermal conductivity and sound absorption are porosity, density, and microstructural design, and these apply to all the systems [50].

5. STANDARDIZATION, DURABILITY, AND SCALABILITY CHALLENGES

The lack of properly developed standards for additive manufacturing (AM) in terms of 3D printed polymers is a significant barrier to increased acceptance in industrial use. The ISO TC261 and ASTM International areas of AM standards are being created, yet the majority of current standards for materials used in AM continue to reference conventional manufacturing methods of production and do not take into consideration the specific prints (or printing parameters) of each material, anisotropic behavior, or multi-scale structural features associated with Fused Deposition Modelling (FDM) processes [51-53]. As a consequence of these issues, polymer AM standards have fallen considerably behind that of metals and, therefore, have not produced consistent quality of products and have not developed reliable test methods for these products [54, 55]. In addition to the standardization issue, additional issues of scalability exist within both AM and the manufacturing processes used in AM. These issues address the ability of AM processes to produce durable materials, maintain process consistency, consume a large amount of energy, and produce quality control products on a continual basis when scaled [56-59]. For large format 3D printing, close monitoring of the AM process is required in order to prevent defects from occurring and will be complicated by ongoing technical issues such as appropriate material selection, interlayer bonding, speed/quality trade-off decisions, and thermal shrinkage [60, 61]. Realizing the full potential of AM is constrained by several factors, including a lack of sophisticated computational design tools, a limited selection of generic material feedstocks, and insufficient in-situ monitoring techniques [62]. Furthermore, accurately predicting the thermal behavior of 3D-printed structures requires advanced numerical models that can account for inhomogeneous porosity, anisotropy, and surface roughness.

6. HYBRID SYSTEMS, MULTIFUNCTIONALITY, AND FUTURE DIRECTIONS

Future advancements in 3D-printed insulation will likely stem from innovations in materials, design, and manufacturing processes. Key areas of opportunity include multi-material printing, smart systems, and the establishment of clear performance benchmarks.

6.1 Multi-material and hierarchical architectures

Using multiple materials to create three-dimensional prints allows for the creation of structures that have multiple layers, which can help improve both the insulation qualities of heat and sound, and are typically designed after observing nature's designs. By following the basic principles of natural design and taking into account how nature has combined many different materials together in order to create stronger and more functional composite materials, we can produce some of the best-performing and most versatile materials on the market today [63]. To date, hierarchical porous structures have been utilized effectively for performing thermal management tasks. Examples include creating ceramics using clay as a base material combined with a foam-like ink that has been stabilized with particles, resulting in creating hierarchical structures with micropores that are controlled by the temperature at which the ceramics are sintered and that create thermal insulating and evaporative cooling properties [64]. In addition, the use of cellular structures created by 3D printing has enabled lightweight products to be made from materials that combine a combination of high mechanical strengths and specific thermal and acoustic response characteristics based on porosity [65]. One extremely unique and innovative application developed is the development of hybrid silica voxels, which are porous silica particles combined with elastomeric materials. These hybrid silica voxels have been demonstrated to have a very low thermal conductivity (19.1 (W/m·K)) and possess mechanical flexibility with tunable strength (71.6 kPa to 1.5 Mpa) [66-76]. These innovative approaches hold great potential for building thermal management applications as well as battery thermal aging.

6.2 Smart and 4D printing for adaptive insulation

Smart polymers with shape memory, self-healing, or stimuli-responsive porosity features can be the reason for adaptive insulation, e.g., tunable vents or panels that stiffen under dynamic loads [67-70]. Low electrical, magnetic, or photothermal power can be used for indirect heating to actuate 4D printed elements [71, 72]. But it will take a hefty amount of progress in material robustness, safety, and lifecycle validation to make this technology feasible for applications at the scale of buildings.

Four-dimensional printing is an emerging additive manufacturing technology that combines 3D printing along with the usage of smart materials that undergo time-dependent transformations in response to a variety of external stimuli such as heat, moisture, pH, magnetic fields, or light [73, 74]. The range of applications includes deployable structures for the polar regions, tissue engineering, and drug delivery systems [75, 76], thus, the potential of building envelopes that adjust to environmental conditions.

6.3 Benchmarks and comparative studies

The advent of functional 3D printing is an innovative technology for creating multidimensional functional materials that can be tailored to numerous applications, such as sensors, actuators, and construction materials [38]. Thermal conductivity values have been reported for a variety of AM processes and materials ranging from 0.03 to 0.09 (W/m·K), e.g., silivoxel composites, cellulose nanocrystals, PU-cork, etc., and PLA lattices can exhibit k ≈ 0.037 (W/m·K) and STL ≈ 48 (dB) [11]. Based on LCA data, there are potential energy savings ranging from 45% to over 67% over an 8.5-14.8-year payback time with optimized panel thicknesses of approximately 4-10 mm for typical building conditions [11]. A new category of functional composite materials that incorporate either conductive or sensing components has great potential for developing integrated condition monitoring solutions [74].

7. CRITICAL DISCUSSION AND RESEARCH GAPS

This section provides a critical assessment of the current state of research, discussing performance trade-offs, material limitations, and future research priorities.

7.1 Thermal–acoustic coupling and trade-offs

These substances act as two-way insulators, combining heat insulation with sound absorption capabilities. PLA panels have been shown to be multifunctional and adjustable by infill density; however, their thermal capability is quite limited in comparison with advanced aerogels.

Just in case, Polyimide aerogels and their SiO_2 hybrids provide the brilliant results, among them ultra-low thermal conductivity and broadband sound absorption; still, their scalability and production cost are the biggest issues [75].

Biodegradable composites sourced from agricultural waste and natural fibers are a renewable direction with decent thermal–acoustic performance, but most of the time, they are devoid of standardized testing protocols and the longevity of the product is not known.

Nonwoven materials, whether PP, PET-based, or aerogel-filled, can be referred to as good-price solutions but their thermal conductivity is, in general, higher than what is expected. Lastly, panels made from reused and recycled materials illustrate the advantages of a circular economic model, even though their performance is lower than that of the engineered systems [76].

While several types of materials show promise, no one material type is able to meet low cost, high thermal-acoustic efficiency (TEA), durability over time, and the ability to be manufactured in a large scale and commercially. Studies reporting excellent thermal insulators (such as aerogel) or extremely high levels of acoustic absorbency (like bio composites) exist; however, there are virtually no studies demonstrating the ability to produce both at a commercially viable level. This gap in the literature indicates that future research needs to develop hybrid systems that incorporate both structural control (through infill patterns and porosity) as well as environmentally friendly design, in order to provide an optimized multifunctional solution [77] (Tables 1 and 2).

Table 1. Comparative relationship between structural parameters and functional properties

Structural Parameter	Thermal Effect	Acoustic Effect	Optimal Range
Infill Density [7]	Lower density reduces thermal conductivity	Intermediate density enhances sound absorption	40–60%
Unit Cell Size [20]	< 6 mm suppresses convection	<5 mm improves high-frequency absorption	5–8 mm
Geometry Type [13]	Honeycomb and gyroid extend heat paths	Gyroid enhances broadband absorption	Gyroid preferred
Porosity [8]	Higher porosity decreases k	Higher porosity increases α up to saturation	50–70%
Material Type [34]	PLA, aerogels yield low k values	PLA and bio-composites yield high α	PLA, aerogel hybrids

Table 2. Summary of previous researches on the performance of materials for thermal as well as acoustic insulation

Ref.	Year	Material /Geometry	Focus	Key Findings
Tychanicz-Kwiecień et al. [7]	2025	PLA, PET-G, ABS	Thermal (infill density)	Thermal conductivity lowered by ≈30% when density reduced from 100% to 40%.
Krapež Tomec et al. [8]	2024	Wood–PLA	Thermal (composites)	Significant decrease in conductivity and diffusivity with increased porosity.
Lopes et al. [9]	2023	PET-G (cubic, honeycomb)	Thermal (geometry)	Internal geometry altered conduction path, improved insulation.
de Rubeis et al. [10]	2022	PLA blocks (square vs honeycomb)	Thermal (U-value)	Honeycomb cells achieved the lowest U-value.
Islam et al. [11]	2023	PLA panels	Thermal + Acoustic	Best performance at medium infill densities (40–60%). k ≈ 0.037 W/m·K, STL ≈ 48 dB.
Anwajler et al. [12]	2024	Gyroid (TPMS)	Thermal (advanced geometry)	Very low thermal conductivity (0.023–0.039 W/m·K).
Zaharia et al. [17]	2023	PLA	Acoustic (infill density)	Optimum absorption at 40% infill (α ≈ 0.93 at 2500 Hz).
Pop et al. [24]	2025	PLA (shell + infill)	Acoustic	Shell + infill design achieved α ≈ 0.99; infill-only achieved STL ≈ 53 dB.
Monkova et al. [19]	2022	PLA (triangular, circular)	Acoustic (geometry)	Reduced sound reflection by up to 40%.
Rivera-Salinas et al [20]	2021	PLA (nozzle 0.8 mm)	Acoustic (pattern)	Highest absorption in the mid-frequency range.
Godakawela et al. [21]	2025	Gyroid TPMS	Acoustic	Achieved α > 0.85 across 1000–4000 Hz.
Hrițuc et al. [22]	2023	Lattice (review)	Acoustic	3D lattices balance stiffness and high sound absorption.
Pop et al. [30]	2024	Biocomposites	Dual (eco-friendly)	k ≈ 0.045 W/m·K, α > 0.7.
Segura et al. [31]	2024	Fruit waste panels	Dual (eco-friendly)	k ≈ 0.036–0.04 W/m·K, α > 0.8.
Ali et al. [32]	2024	Tea bag + palm fibers	Dual (eco-friendly)	Lightweight with high sound absorption.
Usta et al. [33]	2025	PET nonwoven	Dual (low-cost)	R-value ≈ 0.12 m²·K/W, α ≈ 0.78.
Katsura et al. [34]	2024	Nonwoven + aerogel	Dual	k ≈ 0.03 W/m·K, α ≈ 0.85.
Neri [36]	2022	Recycled polyester	Dual (recycled)	Lower performance than PLA but environmentally friendly.

7.2 Material limitations and characterization needs

Research into the application of polymeric materials produced with 3D printing technologies to support the thermal insulation of buildings has identified multiple limitations within the current available materials and remaining challenges faced by manufacturer's developing these products. 3D Printing satisfies the criteria for enhanced design capabilities and capacity/performance similar to traditional technology supporting thermal insulation product requirements, utilizing materials with thermal conductivities that can be as low as 0.03-0.08 (W/m·K) [78]. However, there are still fundamental physical limitations of the existing materials, as well as many materials are lacking functional properties due to the requirements of 3D Printing materials to possess physical properties compatible with the 3D Printing process, thereby restricting the materials available for use [79]. The process of production of these products has become problematic because of the existence of defects associated with print processes (such as warping and interlayer delamination), coupled with the complexities of the production of 3D Printed insulation products on a larger scale, are major hindrances to the advancement of the industry. Furthermore, there are limited results of scientific research evaluating innovative testing methods such as Dynamic Mechanical Analysis and Impact Testing for the purpose of determining the appropriateness of potential use in real-world applications [80].

7.3 Future research priorities

While polymer materials made by 3D printing have recently been improved to a point where they show a lot of promise, there are still indispensable gaps in the research. Hence, research in the near future should chiefly focus on the following areas:

1. Expansion of Printable Materials: Arguably, expanding the library of printable materials is the single most important thing that needs to be done, especially materials with inherent insulation properties and those of sustainable origins. To develop novel nanocomposite polymers that are not only environmentally friendly but also have improved features, a combination of different fields of science is necessary [81].

2. Optimization of Polymer Chemistry: The first goal of the research should be the optimization of polymer chemistry, specifically in AM processes, thus achieving improved interlayer adhesion, fewer defects, and longer durability which is also accompanied by fire resistance [82].

3. Integrated Design and Modeling: The integration of material science, processing optimization, and multifunctional design strategies are some of the future ways that can be used to develop the products further [83]. Apart from that, this also involves the development of physical models that can efficiently predict thermal, acoustic, and mechanical properties in the coupling while considering the manufacturing effects.

4. Lifecycle and Sustainability Analysis: Detailed Life Cycle Assessments (LCAs) should be carried out to measure the environmental advantages of 3D-printed insulators versus traditional ones.

8. CONCLUSIONS

The recent development of 3D printed porous polymers exhibiting thermal conductivities (between 0.03–0.08 W/m.K) and sound absorption (up to 0.9) demonstrates versatility within multiple use categories, with optimal thermal and sound absorption performance occurring between 40–65% infill density, in certain structures (i.e. gyroid/honeycomb), and porosities (i.e. <8 mm). However, there still exist fundamental issues regarding the potential of 3D printed porous polymers, including a lack of standardization and scalability.

Theoretical models are currently being developed to assist in validating the experimental results obtained to date by demonstrating how the tortuosity and anisotropy of a porosity affect its thermal and sound insulating performance. The systems being developed include; PLA lattices, hybrid polymer-aerogels, and eco-friendly composites using bio-fibres, agricultural residues, and recycled non-woven fabrics. Although the combination of these materials provides a multitude of pathways toward dual-functional insulation, substantial barriers remain. These barriers include, but are not limited to, developing standardization for AM technology, ensuring the longevity and fire safety of 3D printed porous polymers during their expected service life, developing sustainable, large-scale processes to produce 3D printed porous polymers that are both cost effective and reliable, and developing a predictive model that integrates thermal, acoustic, and mechanical performance.

Future advancements are expected to come from the development of multi material/hierarchical structures, adaptive or four-dimensional printing systems, and formal lifecycle assessments, which create new opportunities for developing lightweight, tunable, and scalable building insulation types for construction and other fields.

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