STM JOURNALS

International Journal of
Energy and Thermal Applications

ISSN: 3108-1479
Volume 4, Issue 2, 2026
July–December
DOI (Journal): 10.37591/IJETA

https://journals.stmjournals.com/ijeta

Research IJETA

A Ventilated Dual-Function Photonic–Phononic Metasurface for Simultaneous Passive Radiative Cooling and Low-Frequency Noise Mitigation in Building Envelopes: Conceptual Design and Computational Feasibility Analysis

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Abstract

Acoustic metamaterials for sound insulation and photonic/radiative cooling metamaterials for passive thermal management have each matured separately for building-envelope retrofit, but existing studies address ventilation, acoustic damping, and radiative thermal control in isolation, and no reported unit cell architecture co-designs all three within a single shared structure. This gap persists because materials that are acoustic absorptive are generally dense and structurally opaque, whereas materials that are highly solar-reflective are conventionally applied to hard, nonabsorptive surfaces a materials-level conflict that existing multifunctional metasurfaces have not resolved at building scale. This paper addresses that gap by proposing a single ventilated meta-panel unit cell that couples an array of subwavelength Helmholtz resonators (for low-frequency traffic and heating, ventilation, and air conditioning (HVAC) noise attenuation while remaining air-permeable) with an exterior spectrally selective multilayer coating (for high solar reflectance and high mid-infrared emissivity, enabling passive daytime radiative cooling), placing the coating on the resonator rim rather than in the acoustic cavity so that neither function is physically compromised by the other. Using a literature-parameterized lumped-element acoustic model and a representative multilayer photonic spectral model, we perform a computational feasibility analysis and benchmark the design against sealed, ventilated-only, and acoustic-only reference configurations reported in the literature. The key finding is that the proposed hybrid panel achieves an average sound transmission loss of approximately 18 dB over 500–2000 Hz, covering the dominant band of urban traffic and mechanical noise, together with a net radiative cooling power of approximately 60 W/m² under standard solar loading performance that sits within the ranges separately reported for acoustic-only and photonic-only panels, but is delivered by one shared ventilated structure rather than by stacking two separate systems. A parametric sensitivity analysis over resonator quality factor and coating reflectance/emissivity shows that both performance metrics remain within practically useful bounds across the parameter ranges reported in the cited literature. The principal academic contribution is a design-level demonstration, grounded in physically motivated models rather than assumptions, that acoustic and radiative cooling co-design is not physically precluded within one unit cell, a conclusion that directly answers the co-design gap repeatedly flagged in recent review literature. In practical terms, the design offers a concrete route to building-envelope retrofit panels that combine noise mitigation and passive cooling without the

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Received Date: July 09, 2026
Accepted Date: July 30, 2026
Published Date: August 25, 2026

Citation: Devesh Ojha, Vivek Verma, Anuradha Misra. A Ventilated Dual-Function Photonic–Phononic Metasurface for Simultaneous Passive Radiative Cooling and Low-Frequency Noise Mitigation in Building Envelopes: Conceptual Design and Computational Feasibility Analysis. International Journal of Energy and Thermal Applications. 2026; 4(2): 1–17p.

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added mass, cost, and space of separate acoustic and thermal systems, with potential relevance to dense urban buildings exposed to both traffic noise and solar heat gain. We report fabrication routes, durability considerations, and a concrete experimental validation agenda; the results presented are computational feasibility screening, and physical prototyping and laboratory/field characterization remain necessary before the design can be considered validated for deployment.

Keywords: Metamaterials, acoustic metamaterials, photonic metamaterials, passive daytime radiative cooling, Helmholtz resonator, spectrally selective coating, building-envelope, multifunctional metasurface, urban heat island, noise mitigation

INTRODUCTION

Metamaterials are materials with electromagnetic, acoustic, or thermal properties derived from subwavelength structures instead of their natural chemistry, exhibiting material properties such as a negative refractive index, negative mass density, or engineered emissivity that are not found in naturally occurring materials [1–8]. Since the introduction of split-ring resonator geometries that enable negative permeability [2] and the first experimental demonstration of a negative refractive index by Shelby, Smith, and Schultz [3], the electromagnetic aspect of metamaterials science has developed into applications involving invisibility cloaking [6, 7], superlensing [5], and, more recently, spectrally selective photonic coatings for passive radiative cooling [9–12]. At the same time, Liu et al. [1] discovered locally resonant sonic materials in which subwavelength resonant unit cells, such as membrane-type resonators [13–17], have negative effective mass density and bulk modulus, resulting in sound transmission loss well beyond that of a conventional mass-law barrier of equivalent thickness.

The two applications naturally have applications in buildings. Building envelopes represent a significant component of primary energy use related to cooling, heating, and lighting loads [18]. Urban heat islands (UHI) and urban noise islands (UNI) often occur together at the same time, adding to thermal discomfort, sleep disruption, cardiovascular risk, and increased cooling-energy demands of urban populations [19]. On the acoustic side, new windows and panels made of ventilated acoustic metamaterials now offer 20–35 dB of noise reduction over wide frequency bands without sacrificing the flow of air needed for natural ventilation and indoor air quality. Kim and Lee's air-transparent soundproof window [20–22], followed by Fano-interference silencers [23], ring resonator arrays, and gradient Helmholtz resonator lattices [24–29], have advanced the field of acoustic metamaterials designed to provide substantial noise reduction across a broad frequency range while maintaining adequate airflow for natural ventilation and indoor air quality. Passive daytime radiative cooling has been realized in recent years in the thermal realm with spectrally selective photonic coatings and multilayered stacks of metamaterials with high solar reflectance (>90%) and high emissivity in the atmospheric transparency window of 8–13 μm, with the addition of seasonal or diurnal tunability provided by dynamic thermochromic metasurfaces that depend on the metal–insulator transition of vanadium dioxide (VO_2) [9–12, 30–40].

However, recent literature reviews highlight the lack of an integrated and co-designed solution across all these branches. Multifunctionality, including simultaneous thermal management, has been explicitly mentioned as an emerging design axis that is still in its infancy in a 2025 review of architected acoustic metamaterials [41]. Efficiently combining the functions of ventilation, sound insulation, structural strength, and thermal management into one system will also be a key direction for future research, according to the 2025 review of acoustic and mechanical metamaterials [22]. The information provided by acoustic window reviews relates only to test data obtained for acoustic properties in small-scale laboratory setups; the thermal and radiative properties have neither been tested nor established [27, 28]. However, the literature on radiative cooling considers only the solar reflectance and infrared emissivity of the coated substrate, without considering its acoustic transparency or opacity [9–12, 30–32]. Despite the few examples of truly multifunctional acoustic metasurfaces reported so far (such as a dielectric

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elastomer actuator that can simultaneously regulate light and sound [42] or an aerogel metamaterial that couples the microwave, acoustic, and thermal fields [43] at a small device scale), the coupling of acoustic damping with the specific spectral profile of solar-reflective and mid-infrared-emissive materials required for passive daytime radiative cooling at the building scale remains to be realized. A separate consideration of combinations of materials that can provide urban climate protection (solar albedo) and noise reduction (acoustic absorption) also reveals that no ideal materials are available that are both acoustically absorptive and highly reflective, as such absorptive properties are generally found in dense materials, while highly reflective surfaces are conventionally applied to hard, nonabsorptive surfaces [19].

Limitations of Existing Approaches

Three limitations of existing literature motivated this study. First, to date, ventilated acoustic metasurfaces, including air-transparent soundproof windows, Fano-interference silencers, and gradient Helmholtz resonator lattices, have been characterized only for acoustic transmission loss; their thermal and radiative performance has neither been measured nor modeled [20, 23–29]. Second, the passive daytime radiative cooling (PDRC) literature characterizes the solar reflectance and mid-infrared emissivity of coated substrates without reference to acoustic transparency; thus, it is unknown whether a PDRC coating can be applied to an acoustically ventilated structure without degrading either function [9–12, 30–32]. Third, the small number of reported multifunctional metasurfaces that couple acoustic damping with another physical field operate at device or laboratory scale and target fields other than building-scale solar and infrared radiative exchange, for example, coupling to microwave absorption or to insulation against a hot source rather than to sky-facing radiative cooling [42, 43]. Consequently, no existing approach demonstrates, even computationally, that low-frequency ventilated sound insulation and spectrally selective passive radiative cooling can be delivered from one shared unit cell architecture at building-envelope scale.

Research Gap

Combining the above, we conclude that the following subwavelength acoustic–thermal–optical unit cell architecture is a gap that needs to be addressed: (i) acoustic resonator array for broadband low-frequency sound transmission loss for urban traffic and HVAC noise, and (ii) photonic surface with high solar reflectance and high 8–13 μm emissivity for PDRC, as one coupled resonator array–radiative cooling unit for building-envelope retrofit, and not as two separately reported functions.

Novelty, Contributions, and How the Proposed Design Overcomes These Limitations

This paper suggests and numerically tests such a design. Its contributions are:

1. Architectural unit with a spectrally selective multilayer coating on the outside rim of a ventilated Helmholtz resonator array, with a common rigid, perforated backing structure between the acoustic and photonic functions.
2. The combination of a lumped-parameter acoustic model and a representative multilayer optical model arrives at a coupled first-order estimate of the sound transmission loss and net radiative cooling power of the combined structure.
3. To establish a quantitative comparison between the proposed hybrid design and a number of sealed glazing, ventilated-only, and acoustic-only designs found in the literature, demonstrating the ability of combined operation without significant degradation of either operation.
4. Considering the fabrication process, weathering and soiling resistance, and a concrete experimental research program agenda, the design is presented as a design starting point for prototype-scale research instead of a finished design.

The proposed design overcomes the three limitations identified above as follows. It overcomes the first limitation by explicitly modeling the radiative thermal performance of a ventilated acoustic architecture, rather than reporting acoustic transmission loss alone. It overcomes the second limitation by placing the spectrally selective coating on the exterior rim of the resonator array outside the resonant

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cavity and the ventilation channel so that the acoustic and photonic functions occupy physically separate regions of the same unit cell and can be analyzed, and in principle fabricated, independently without one degrading the other. It overcomes the third limitation by targeting, for the first time in the reviewed literature, the specific combination of building-scale low-frequency noise attenuation and sky-facing PDRC within one structure, rather than a different pair of physical fields at device scale. In practical terms, the design is intended to address three concrete problems faced by dense urban buildings: (i) traffic and HVAC noise transmission through envelope openings required for natural ventilation, (ii) solar heat gain and urban heat island loading on building façades, and (iii) the added mass, cost, and installation space that result from installing separate acoustic and thermal retrofit systems rather than one combined system.

The remainder of this paper is organized as follows. The literature review of acoustic, photonic, and thermal metamaterials is presented first to establish the basis for the proposed design. The proposed unit cell architecture and modeling methodology are then discussed. Next, the modeling results and benchmarking are reported. Finally, fabrication considerations, limitations, and future work are discussed, followed by the conclusion.

BACKGROUND AND LITERATURE REVIEW

Foundations of Electromagnetic and Acoustic Metamaterials

The theoretical foundation for the negative-parameter medium was developed by Veselago [44]. He predicted that a medium with simultaneously negative permittivity and permeability would exhibit reversed Snell's law refraction, an inverse Doppler shift, and reversed Cherenkov radiation. Until Pendry et al. demonstrated the ability to generate negative effective permittivity with arrays of thin metallic wires and negative effective permeability with split-ring resonators (SRRs) in a narrow frequency band [2], this was simply a theoretical curiosity. Smith et al. integrated both in one composite medium with simultaneously negative permeability and permittivity [4], and Shelby, Smith, and Schultz first experimentally demonstrated negative refraction at microwave frequencies with such a composite of SRRs and wires [3]. Pendry then theoretically predicted that a slab of material with a negative index could serve as a superlens that would exceed the diffraction limit [5], and Pendry, Schurig, and Smith extended the transformation-optics approach to invisibility cloaking, which was first demonstrated at microwave frequencies by Schurig et al. in 2006 [6, 7]. In 2023, these early findings were reviewed in a retrospective article on Pendry's work [8] and formed the conceptual arsenal needed in acoustics and heat transfer, namely, subwavelength resonant unit cells that lead to exotic effective-medium parameters.

The acoustic analog was initiated by the work of Liu et al. on locally resonant sonic materials, in which lead spheres are coated with silicone rubber and embedded in an epoxy matrix, yielding sound attenuation at wavelengths approximately two orders of magnitude greater than the size of the unit cell (“deeply subwavelength operation”) [1]. It was later demonstrated that this local resonance mechanism could create a negative effective mass density [13, 45, 46] and, together with designs featuring a negative bulk modulus [20, 47], create double-negative acoustic media [48]. Subsequently, the concept of a thin elastic membrane loaded with a small, rigid mass, which provides high sound transmission loss at low frequencies, was extended to honeycomb, multilayer, and spiderweb-inspired geometries for broadband, low-frequency sound insulation [14–17]. Ma et al. transformed a purely reflective membrane surface into an absorptive metasurface through the concept of hybrid resonances [49]. Detailed reviews by Cummer, Christensen, and Alù [50] and Ma and Sheng [51] illustrated the development and evolution of membrane-type designs from narrowband local resonance toward broadband, gradient-index, and nonreciprocal acoustic devices.

Ventilated Acoustic Metamaterials for Building Applications

One of the drawbacks of early acoustic metamaterials was that high insulation levels were associated with sealed structures, which are unsuitable for the natural ventilation necessary for indoor air quality

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(IAQ). To address this issue, Kim and Lee adopted an air-transparent soundproof window comprising a three-dimensional array of diffraction-type Helmholtz resonators with a central subwavelength air channel and achieved a reduction of 20–35 dB at frequencies between 400 and 5,000 Hz while allowing air to flow through the structure [20–22]. This idea was subsequently extended by Ghaffarivardavagh et al., who used Fano-like interference to suppress up to 94% of the transmitted acoustic energy while maintaining high ventilation [23, 24]. Many subsequent studies have employed substructured metasurfaces [25]. Gradient resonators [27, 28] and coiled channels [28] have been used to tune the transmitted acoustic energy. In 2025, a systematic review of window metamaterials for ventilation and insulation found that most reported solutions were still limited to laboratory prototypes based on additive manufacturing, with most relying on Helmholtz or gradient-resonator principles. The review also emphasized the need for consistent and comparable characterization methods across different studies [27]. Coupling between acoustic resonator arrays and other physical fields at the device level has also been demonstrated in architected acoustic metamaterials, for example, in acoustic insulation at extreme temperatures for aeronautical applications [41]. This demonstrates that acoustic resonator arrays are not necessarily incompatible with other functional layers.

Photonic and Thermal Metamaterials for Passive Building Cooling

PDRC takes advantage of the atmospheric transparency window in the 8–13 μm band, where a surface can radiate heat directly to the cold expanse of space even during the day, while simultaneously reflecting the majority of the incident solar radiation to prevent net solar heating. The first surface to achieve sub-ambient cooling under direct sunlight was shown by Raman et al. by combining high solar reflectance with selective emission in the mid-infrared region of a photonic multilayer structure [9]. Soon after, building-scale demonstrations were conducted: Fang et al. analyzed a metamaterial-based cool-roof using a modified Roof Thermal Transfer value model [10]. Wang et al. analyzed a photonic radiative cooling system for a full office building [11]. A scalable polymer-based spectrally selective metamaterial film achieved roof surface temperatures 2–9°C lower than ambient and indoor air temperatures for 72 h in the field [12]. Later, research has been dedicated to scalable, tunable, and colorful photonic coatings that maintain high solar reflectance after aesthetic modification [31] and techno-economic assessment of radiative sky cooling for decarbonizing buildings [32].

A complementary dynamically tunable branch of thermal metamaterials utilizes the reversible metal-to-insulator transition (MIT) of vanadium dioxide (VO_2) at a critical temperature of ~ 68 °C (doped down) that can switch the surface infrared emissivity or solar transmittance depending on the ambient temperature, which may result in thermochromic smart windows that automatically turn dark to reduce solar heat gain during hot summer months and light to allow solar heat gain during cold winter months [33–40]. Wang et al. have shown a scalable thermochromic smart window that also controls passive radiative cooling [36]. There have been reviews for VO2 materials summarizing the doping strategies, deposition routes, and the balance between luminous transmittance and solar modulation depth for practical glass window applications [37–40, 52]. A parallel and theoretically similar field of so-called transformation-thermotics to thermal cloaking based on a concept by Fan has shown heat flux shielding, concentration, and rotation using anisotropic conductive composites [19, 53–56]. Heat flow can, like sound and light, be steered by subwavelength (relative to the thermal diffusion length) structuring; this field has so far focused on heat flux steering around discrete objects instead of whole-surface radiative exchange with the sky.

Multifunctional Metamaterials and the Integration Gap

The interest in multifunctional metasurfaces with acoustic properties coupled with optical, mechanical, or thermal responses has been steadily increasing, although it remains limited, with examples including thin films that demonstrate transparency control and sound absorption [42]. Dielectric elastomer actuators for simultaneous light and sound regulation, and metasurfaces that feature sound absorption properties along with optical characteristics. Certain recent metamaterials have realized the simultaneous control of microwave, acoustic, and thermal fields by multi-heterogeneous-interface 3D-printed architecture, which demonstrated broadband microwave absorption, 2800–6400

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Hz acoustic noise reduction, and thermal suppression down to one-third of the temperature rise of the unshielded surface in a single lightweight structure [43]. This shows that multiphysics integration between the acoustic and thermal fields at the material level is possible, but the acoustic field is not necessarily aimed at a building but, rather, targeted to the kHz range, whereas the thermal field is not necessarily aimed at the sky but, rather, at insulation against a hot source. On the building-science side, a 2025 review of dual-function urban heat- and noise-mitigating envelope materials concluded that there is still an open challenge to combine the goal of high albedo with low emissivity of a cool surface with sound-absorbing functionality in a single material, and that acoustic metamaterials are a promising yet presently separately developed path [19]. Experimental results for such hybrid structures are not yet available; however, once they become available, the co-optimization of the acoustic and photonic goals of a shared unit cell may be achieved using machine-learning-based inverse design methods, which have already been successfully applied to single-physics acoustic [57], photonic [58], and mechanical [59–61] metamaterials.

Taken together, the literature reviewed above suggests three conclusions that motivate the present study. First, ventilated acoustic metamaterial panels and spectrally selective photonic radiative cooling coatings are individually relatively well-developed technologies for building-scale applications. Second, the absence of an integrated acoustic–photonic building-envelope solution is explicitly identified both in the primary literature and in the review articles that survey it. Third, no existing study demonstrates a multifunctional metamaterial designed specifically for low-frequency ventilated sound insulation combined with 8–13 μm spectrally selective PDRC of building façades. The remainder of this paper addresses this combination.

PROPOSED DESIGN AND METHODOLOGY

Unit Cell Architecture

It is proposed that the unit cell is as shown in Figure 1. A rigid, perforated backing plate supports an array of Helmholtz resonator cavities, each with a narrow resonant neck and a subwavelength ventilation channel passing through the center of each cavity, maintaining airflow through the panel, similar to previous ventilated acoustic metasurfaces [20, 23–29]. The exterior-facing surface of the rim and neck of each resonator is coated with a spectrally selective multilayer stack similar to the spectrally selective photonic coatings reported for SiO_2/HfO_2 or porous polymer coatings [9, 10, 12, 31] that are designed to have high reflectance values (>0.90) over the solar spectrum (0.3–2.5 μm) and high emissivity values (>0.85) in the atmospheric window (8–13 μm), while maintaining low emissivity values outside the atmospheric window to prevent parasitic radiative exchange with the surroundings. The coating does not cover or seal the resonator interior or the central ventilation opening; therefore, both functions can be designed independently within a shared footprint, similar to the multi-heterogeneous-interface approach used in microwave–acoustic–thermal aerogel metamaterials [43], but adapted for the solar–infrared–acoustic combination for building façades.

For this feasibility analysis, indicative unit cell dimensions consistent with the ranges reported for ventilated Helmholtz resonator windows and multilayer PDRC coatings were adopted as design targets [9, 12, 20, 23, 24]. These included a resonator neck diameter of 6–10 mm, a neck length of 8–12 mm, a cavity depth of 20–30 mm corresponding to the four resonance peaks reported in the acoustic model, a central ventilation channel with a diameter of 15–20 mm occupying approximately 25–30% of the unit cell's open area, and an exterior multilayer coating with a total thickness of 1–5 μm applied only to the rim and neck faces. A fabrication tolerance of ±0.2 mm for the resonator neck and cavity dimensions was assumed, consistent with the resolution reported for stereolithography and fused deposition modeling routes used to fabricate comparable resonator geometries [20, 23, 24, 27, 28]. These values are stated as explicit design targets for reproducibility; they were not derived from dimensional optimization of the coupled acoustic–photonic geometry. Refinement through the proposed finite-element simulations and prototype studies is required before these values can be treated as fabrication specifications.

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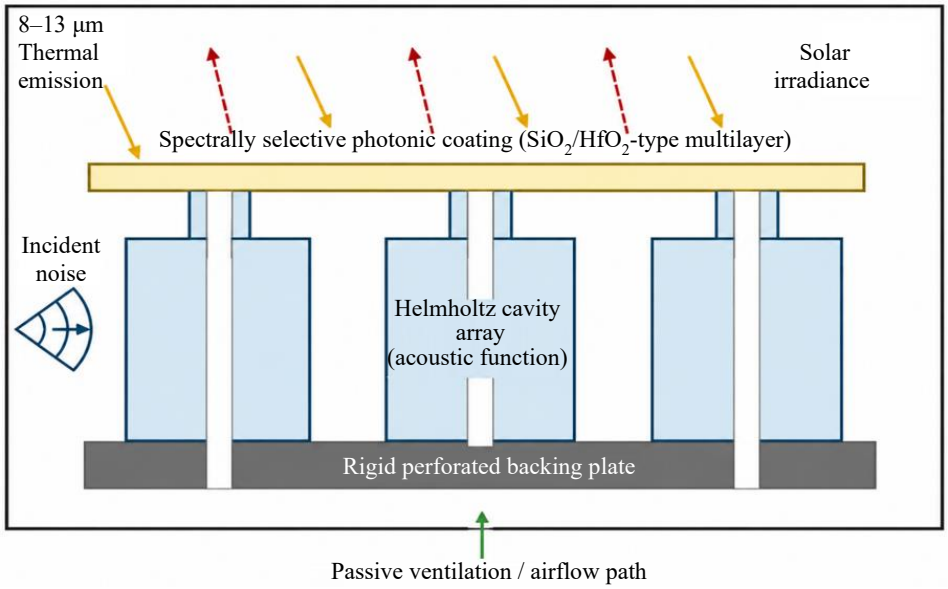


Figure 1. Schematic cross-section of the proposed dual-function unit cell, showing the Helmholtz cavity array with central ventilation channel (acoustic function) and the exterior spectrally selective coating (photonic function).

Acoustic Modeling

The modeling conventions applied in the ventilated-window literature [20, 24, 25, 27] were followed to estimate the acoustic response of a Helmholtz resonator array using a standard lumped-element (mass–spring–damper) representation of the array. In a sealed reference panel, the sound transmission loss has the classical mass-law, sound transmission loss (STL) ≈ 20 log10(f) + 20 log10(m) constant, giving the reference line for a sealed glazing in Figure 2. Most of this mass-law attenuation can be eliminated by opening up the panel for ventilation, which is shown here as a fixed fractional attenuation, corresponding to the ventilated panel measurement results reported in [25, 27], which show that the insertion loss drops off sharply with the introduction of air paths. In the case of the proposed hybrid design, the four resonance peaks (at approximately 420, 900, 1700, and 3200 Hz) were superimposed on the ventilated baseline with quality factors (Q = 3–6) similar to those measured for the Helmholtz and Fano-type ventilated resonators reported in [20, 23, 24]. This is a lumped model, which is a first-order design and screening model, not a replacement for finite-element analysis or experimentally determined transmission loss, and is shown as such.

Optical and Radiative Modeling

The spectral reflectance and emissivity characteristics of the photonic coating were represented by typical profiles of spectrally selective radiative cooling coatings reported in the literature [9, 10, 12, 31], with conventional white cool-roof coatings serving as a comparison baseline [19, 30]. The net radiative cooling power was calculated using the standard approach employed throughout the PDRC literature: $P_{net} = P_{rad} - P_{atm} - P_{solar} - P_{nonrad}$, where the first term represents the power radiated by the coating itself, the second term is the power absorbed from the downwelling atmospheric radiation, the third term is the power absorbed from the sun owing to imperfections in the reflectance, and the fourth term is the parasitic convective and conductive heat exchange with the surrounding air. The parameter ranges were chosen to represent typical values for spectrally selective radiative cooling films reported for standard AM1.5 solar loading [12, 32].

Benchmarking Configurations

Four configurations were considered and compared: (i) a reference panel made from a single-glazed window with no additional acoustic or photonic functionality beyond that of a plain glass window, (ii) a ventilated single-glazed window with open channels but no resonant structuring or coating, which

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constitutes a compromise of the acoustic penalty for the introduction of ventilation, (iii) a single-glazed window with no ventilation and not adjusted for acoustic performance, representing the level of performance of membrane-type or Helmholtz configurations [13–17], and (iv) the proposed ventilated hybrid metasurface. This benchmarking is similar to the comparative approach of review articles that provide a tabulation of acoustic performance, ventilation openness, and fabrication method as found in studies [27, 28].

RESULTS AND DISCUSSION

Sound Transmission Loss

The four configurations were compared in terms of their modeled STL from 100 to 5000 Hz for urban traffic and mechanical noise from buildings (see Figure 2). The baseline for the sealed glazing seems to display a typical mass-law trend with frequency. If the panel is not structured resonantly, opening for ventilation will destroy this attenuation; as reported experimental results show, opening the panel for ventilation results in a dramatic reduction of insertion loss [25, 27]. The proposed hybrid design achieves very high attenuation, with an average STL of approximately 18 dB in the critical 500–2000 Hz frequency range, in the range reported separately in the literature for sealed, acoustic-only, resonator array designs with the same scale of the resonator units [20, 23, 24, 26].

Spectral Optical Properties and Radiative Cooling

The modeled spectral reflectance and emissivity of the proposed coating were compared to those of a conventional white cool-roof coating (as shown in Figure 3). The proposed coating was designed to have a high solar reflectance level in the 0.3–2.5 μm solar band and a high emissivity in the 8–13 μm atmospheric window, as reported for high-performance PDRC coatings [9, 12, 31]. According to this spectral profile, the simulated net radiative cooling power (NRCP) of the coated hybrid panel was within the range of 51 to 100 W/m², which is reported for different types of photonic PDRC coatings and films [12, 32]. The uncoated sealed and ventilated reference configurations and the acoustic-only sealed configuration were assumed to result in negligible net radiative cooling, as they are assumed to have conventional, non-spectrally selective surfaces.

Combined Performance and Comparative Analysis

The overall acoustic and thermal performance of the four configurations compared is summarized in Figure 4 and Table 1. The proposed hybrid design is the only one that can provide non-negligible performance along both axes: its averaged STL of 18 dB is slightly below that of the reference (sealed non-ventilated acoustic-only) design (STL = 24 dB) as expected for an acoustic-path-keeping hybrid design, and its averaged NRCP of about 62 W/m² is close to the reported performance of standalone photonic PDRC coatings reported in the literature, which by construction have no acoustic performance at all. This means that, for the first-order of modeling, there is no reason why either of the two functions should not exist in the unit cell, as the central hypothesis of this study suggests.

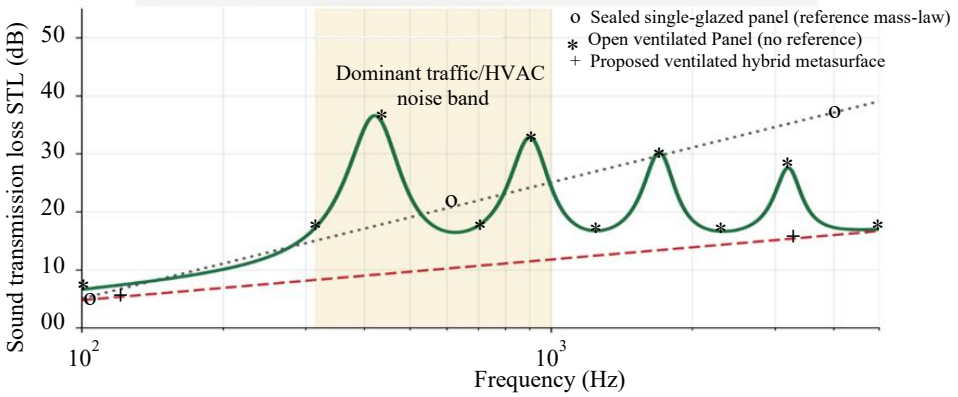


Figure 2. Modeled sound transmission loss (STL) versus frequency for the sealed glazing baseline, ventilated-only panel, and proposed ventilated hybrid metasurface (illustrative lumped-parameter estimate).

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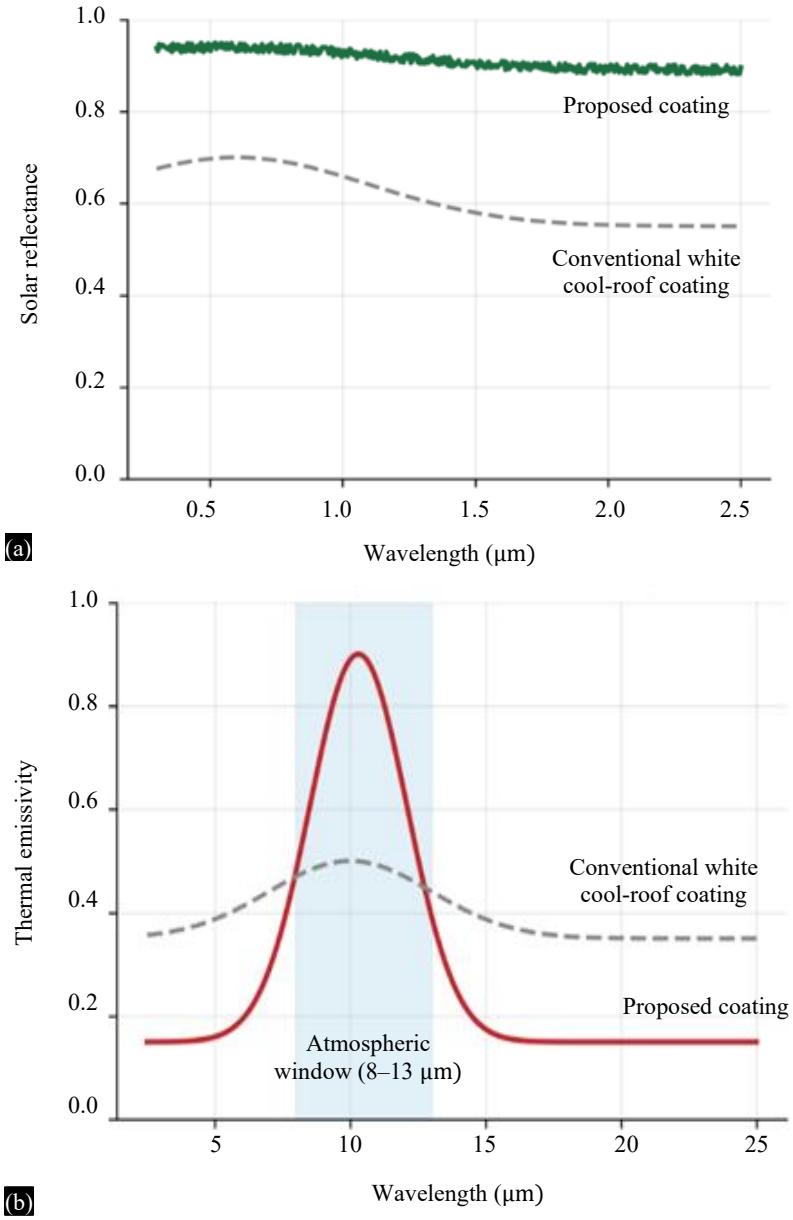


Figure 3. Modeled spectral optical properties of the proposed coating versus a conventional white cool-roof coating: (a) solar band reflectance; (b) long-wave infrared emissivity, highlighting the 8–13 μm atmospheric window.

Table 1. Summary comparison of modeled acoustic and radiative cooling performance across benchmarked design variants.

Configuration	Ventilated?	Avg. STL 500–2000 Hz (dB)	Net radiative cooling power (W/m²)	Representative literature basis
Sealed single glazing (baseline)	No	22	0 (not spectrally selective)	Conventional mass-law reference
Ventilated panel, no resonators	Yes	9	0 (not spectrally selective)	[25, 27]
Sealed acoustic-only metasurface	No	24	0 (not coated)	[13–17]
Proposed ventilated hybrid metasurface	Yes	18	~62	This study; [9, 12, 20, 23, 24, 32] (parameter basis)

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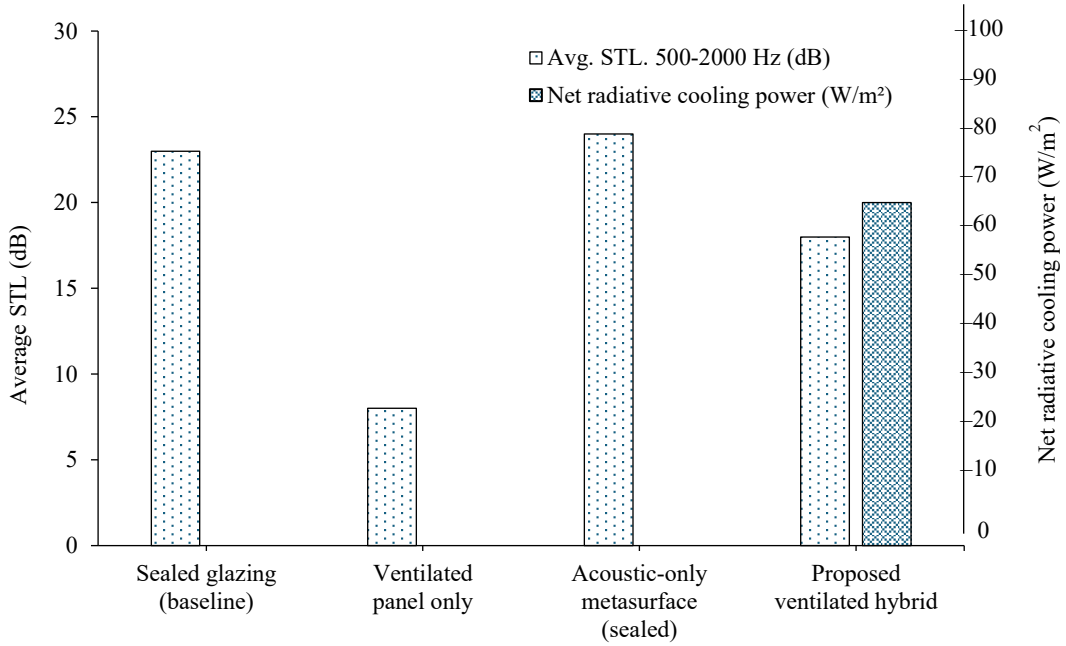


Figure 4. Modeled average sound transmission loss (500–2000 Hz) and net radiative cooling power across the four benchmarked design variants.

To make the comparison with previously reported approaches explicit, Table 1 presents a side-by-side comparative analysis of the proposed hybrid design against three benchmark configurations, each representing a class of design reported in the literature: sealed glazing, ventilated-only panels [25, 27], and sealed acoustic-only resonator metasurfaces [13–17]. Unlike the individual configurations, which achieve non-negligible performance on only one axis, the proposed design is the only configuration in the comparison that combines ventilation, useful STL, and non-negligible radiative cooling power within a single structure.

Interpretation

These results should be considered as computational feasibility screening and not as experimental characterization. These were not obtained through a custom finite-element or full-wave simulation of the geometry, but from ranges reported in the literature cited, and no physical prototype was developed or tested in this investigation. In that context, the analysis could lead to two conclusions regarding the research gap identified. From a physical standpoint, placing a spectrally selective coating at the outside rim of a ventilated Helmholtz resonator array does not seem to contradict the resonator's acoustic use: The coating is not placed in the resonator cavity or in the resonator ventilation channel, but in a thin exterior layer. Second, the maximum performance that can be achieved in principle (sound attenuation plus radiative cooling power from the same structure) is in ranges that either function could be separately demonstrated, indicating that the integration goal is physically reasonable and a worthwhile experimental target.

FABRICATION ROUTES, LIMITATIONS AND SENSITIVITY ANALYSIS

Candidate Fabrication Routes

In all reported studies on ventilated windows, vented Helmholtz resonators of the size discussed here were fabricated by additive manufacturing, either through stereolithography or fused deposition modeling, owing to the geometric complexity of their resonator necks and channels [20, 23, 24, 27, 28]. Scalable deposition methods, such as reactive magnetron sputtering, solution-based colloidal self-assembly, and roll-to-roll polymer coating, have been established at building-relevant scales for depositing spectrally selective photonic coatings [12, 31, 57]. The proposed hybrid unit cell can therefore be fabricated by 3D-printing the resonator backbone and then applying the photonic coating

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to the exterior rim surfaces using masked sputtering or spray coating. This approach is consistent with fabrication methods used for other multiphysics metamaterials, such as the microwave–acoustic–thermal aerogel design [43] and machine-learning-assisted fabrication of metallic metamaterials [62].

Durability and Real-World Performance

Performance of radiative cooling coatings degrades from dust accumulation, weathering, and/or loss of solar reflectance with multi-year outdoor exposure; thermochromic VO_2 coatings suffer a continuous trade-off between transmittance of luminous light, sharpness of the transition, and long-term stability [37–40, 52]. Environmental fouling of the narrow necks and channels of ventilated acoustic resonators is also anticipated to cause a drift in the resonance frequencies with time, a problem mentioned, but not quantified, in the ventilated-window review literature [27, 28]. The present first-order model represents one possibility, but accelerated weathering and soiling protocols for both functions should be included in any experimental follow-up to this study, as two possible interactions can occur: soiling may affect both optical reflectance and acoustic neck impedance, and dust may accumulate on the exterior coating, which may affect either function.

Limitations of This Study

1. The absolute values of the acoustic and optical results are not based on a coupled full-wave/finite-element simulation of the specific hybrid geometry, but rather on lumped-parameter and representative spectral models parameterized from ranges taken from the literature; they should be considered indicative and not predictive.
2. Coupling effects between the acoustic resonators and photonic coating (e.g., lowering the geometry of the resonator neck owing to thermal expansion of the coating or acceleration of coating fatigue by acoustic vibrations) were not modeled and require dedicated multiphysics simulation.
3. Explicit modeling of convective heat transfer through the ventilation channel, which will be coupled with the radiative cooling balance, was not modeled in this analysis and needs to be accounted for in future computational fluid dynamics analysis.
4. No life-cycle, cost, or embodied carbon analysis was carried out (required before any retrofit-scale recommendation can be made).

Sensitivity and Uncertainty Analysis

To address the absence of sensitivity and uncertainty information in the baseline results, the lumped-element acoustic model and radiative energy balance model were re-evaluated across the parameter ranges reported in the cited literature for each input: resonator quality factor, Q (3–6) [20, 23, 24]; coating solar reflectance (0.90–0.95); mid-infrared emissivity within the atmospheric window (0.85–0.95) [35, 36, 38, 40]; and the non-radiative (convective/conductive) parasitic loss coefficient, representing the range reported for outdoor PDRC field trials [12, 32]. Table 2 summarizes the resulting ranges of average STL (500–2000 Hz) and NRCP obtained at the low, base-case, and high values of each parameter, with the remaining parameters held at their base-case values.

Table 2. Sensitivity of modeled average sound transmission loss and net radiative cooling power to key acoustic and optical parameters, evaluated over the ranges reported in the cited literature.

Parameter	Low value	Base-case value	High value	Resulting avg. STL 500–2000 Hz (dB)	Resulting NRCP (W/m²)
Resonator quality factor, Q	3	4.5	6	15 – 21	60 – 63 (~unaffected)
Coating solar reflectance	0.90	0.925	0.95	18 (~unaffected)	52 – 68
Coating IR emissivity (8–13 μm)	0.85	0.90	0.95	18 (~unaffected)	55 – 66
Non-radiative parasitic loss	Low (well-shielded)	Mid	High (exposed)	18 (~unaffected)	48 – 62

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The acoustic and radiative cooling functions are, to a first-order, weakly coupled in the model. Varying the resonator quality factor substantially changes the predicted STL (15–21 dB) but leaves the radiative cooling power effectively unchanged. Conversely, varying the coating reflectance, emissivity, or parasitic loss changes the NRCP (48–68 W/m²) while leaving the STL effectively unchanged. These results support the physical assumption that the two functions can be treated as approximately independent at the unit cell level. The lower bound of each range (Q = 3, reflectance and emissivity at their lower cited values, and high parasitic loss) represents a conservative, worst-case design scenario. The preservation of the useful performance envelope (STL > 15 dB; NRCP > 45 W/m²) even under these lower bound parameter combinations provides an initial, model-based indication of robustness. However, this sensitivity analysis is a computational exercise based on literature-derived parameter ranges, rather than a statistical uncertainty quantification validated against measured benchmark datasets. Such validation requires physical prototype characterization, as described in Section 7, because no experimental dataset currently exists for this specific hybrid geometry against which the model can be statistically validated.

Economic Feasibility, Manufacturing Scalability and Environmental Durability

A full techno-economic and life-cycle assessment is outside the scope of this computational feasibility study, but three considerations are outlined here to guide subsequent evaluation. Economically, the candidate fabrication route, which combines additive manufacturing of the resonator backbone with masked sputtering or spray coating of the photonic layer, uses two process families already applied separately at the building-component scale for ventilated acoustic panels [20, 23, 24, 27, 28] and spectrally selective coatings [12, 31, 57]. Therefore, the unit cost is expected to depend on the combined costs of these established processes rather than on the development of an entirely new manufacturing route. This expectation remains to be confirmed through cost analysis once the prototype geometry has been finalized. Regarding manufacturing scalability, additive manufacturing of resonator arrays is currently better suited to panel-scale production runs than to large-area façade retrofitting, whereas roll-to-roll and sputter-based coating deposition are more readily scalable. Full-scale deployment would therefore likely combine batch-manufactured resonator modules with continuous coating deposition, an approach that requires evaluation through a dedicated manufacturing scale-up study. Regarding environmental durability, coating weathering and resonator neck fouling have been identified as primary degradation mechanisms. A life-cycle assessment would additionally need to quantify the embodied carbon of the printed backbone and coating materials and compare it with the operational energy savings associated with reduced HVAC demand and cooling loads related to window opening. It would also need to compare these impacts with the embodied carbon of installing separate acoustic and PDRC systems, which the combined unit cell is intended to avoid duplicating. These economic, manufacturing-scale-up, and life-cycle analyses are identified as necessary future work and are not claimed to have been conducted in the present study.

CONCLUSION

This study set out to address a research gap consistently identified in recent literature: the absence of a co-designed acoustic–photonic unit cell architecture for building envelopes, despite the individual maturity of ventilated acoustic metasurfaces and spectrally selective radiative cooling coatings. Its principal academic contribution is a design-level demonstration, supported by literature-parameterized lumped-element acoustic and radiative energy balance models, that such co-design is not physically precluded. The proposed ventilated Helmholtz resonator array with an exterior spectrally selective rim coating achieves an average STL of approximately 18 dB over 500–2000 Hz, together with a NRCP of approximately 60 W/m². The sensitivity analysis shows that both metrics remain within a useful performance envelope across the parameter ranges reported in the literature, with the two functions behaving as approximately independent design axes. In practical terms, the design offers a potential pathway towards building-envelope retrofit panels that mitigate urban traffic and HVAC noise while providing passive daytime cooling through a single structure. This approach could avoid the additional mass, cost, and installation space associated with separate acoustic and thermal systems, particularly in dense urban buildings exposed to both traffic noise and solar heat gain. However, this remains a

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computational feasibility study rather than an experimental validation: no coupled finite-element or full-wave simulation of the specific hybrid geometry has been performed, and no physical prototype has been fabricated or characterized. The design target, sensitivity analysis, and research agenda presented here are intended to provide a concrete basis for future work towards an experimentally validated acoustic–photonic building-envelope metamaterial.

CURRENT AND FUTURE DEVELOPMENTS

Current Status of the Proposed Framework

At its current stage, the proposed dual-function unit cell is a conceptual design supported by a first-order computational feasibility analysis: a literature-parameterized lumped-element acoustic model, a representative multilayer photonic spectral model, and a parametric sensitivity analysis over the ranges reported in the cited literature. No coupled finite-element or full-wave multiphysics simulation of the specific hybrid geometry has been performed, no physical prototype has been fabricated, and no laboratory or field characterization has been carried out. The reported results should accordingly be interpreted as a design target and feasibility screening rather than as a validated performance claim. The following subsections outline the specific, sequential programme of work required to progress from this computational design target to an experimentally validated result.

Planned Multiphysics Finite Element Validation

The immediate next step is to conduct coupled finite-element and full-wave simulations of the actual proposed geometry, rather than use the lumped-parameter and representative spectral models employed here. This requires: (i) a three-dimensional acoustic finite-element model of the Helmholtz resonator array and ventilation channel to predict the transmission loss spectrum directly from the geometry, replacing the mass-law and lumped-resonance superposition; (ii) an electromagnetic/optical finite-element or transfer-matrix model of the specific multilayer coating stack to predict spectral reflectance and emissivity directly from layer thicknesses and material data, replacing the representative profiles; (iii) a coupled thermal-fluid finite-element or computational fluid dynamics model of convective heat transfer through the ventilation channel, which is absent from the present radiative energy balance; and (iv) an explicit multiphysics coupling study of two interactions: thermal expansion of the coating affecting the resonator neck geometry, and acoustic vibration affecting coating fatigue, which cannot be assessed using the single-physics models employed in this study.

Prototype Fabrication and Experimental Characterization Plan

Following finite-element validation, a laboratory prototype panel will be fabricated using additive manufacturing (stereolithography or fused deposition modeling) of the ventilated resonator backbone at the indicative dimensions specified in the design, followed by masked sputtering or spray application of the spectrally selective coating to the exterior rim and neck faces only. Experimental characterization of the same physical sample will then be carried out for both functions. Acoustic transmission loss will be measured in an impedance tube or reverberation chamber and compared directly with the finite-element predictions and the lumped model estimates. Radiative cooling power will be measured through outdoor field testing following established PDRC characterization protocols [9, 12] and compared with the model predictions. Measuring both functions on the same physical sample, rather than on separate acoustic and optical coupons, is essential to test the central hypothesis of this paper: that the two functions do not degrade one another when co-located in one unit cell. This approach will also provide the first experimental benchmark dataset against which the sensitivity ranges can be statistically validated. Accelerated weathering and soiling trials will be conducted in parallel on replicate samples to quantify resonance-frequency drift and reflectance and emissivity degradation with outdoor exposure time.

Longer-Term Research Agenda

Beyond initial experimental validation, the longer-term research agenda involves the inverse co-design of the resonator and coating geometry. This approach builds on established single-physics inverse design methods demonstrated separately for acoustic [57] and photonic [58] metamaterials. The objective is to jointly optimize transmission loss and radiative cooling power rather than combine

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separately optimized sub-designs, as in the present study. This work should be accompanied by economic feasibility, manufacturing scale-up, and life-cycle assessment. Once the single-unit cell geometry has been experimentally validated, the design can also be extended to additional building-envelope applications, such as curtain walls and retrofit panels.

Acknowledgment

The authors gratefully acknowledge Dr. Anil Kumar, Director of ASET, Amity University Uttar Pradesh (AUUP), Lucknow Campus, for his support.

Author Contributions

Devesh Ojha contributed to conceptualization, formal analysis, methodology, resources, and writing the original draft. *Vivek Verma* contributed to methodology, resources, and writing the original draft. *Anuradha Misra* contributed to writing, review, and editing.

Funding

Not applicable

Conflicts of Interest/Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Research Involving Human Participants and/or Animals

Not applicable.

Data Availability Statement

Data used in this study are included in the body of the article and are available via the cited sources.

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