

Mechanism of airborne sound absorption through triboelectric effect for noise mitigation

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Mitigating broadband noise with passive airborne sound absorbers has been a long-lasting challenge, particularly for low-frequency anthropogenic sounds below kilohertz with long wavelengths, which require bulky materials for effective absorption. Here, we propose a strategy that utilizes local triboelectric effect and in-situ electrical energy dissipation mechanism for airborne sound absorption. This approach involves a fundamentally different mechanism that converts airborne sound into electricity for energy dissipation, in contrast to conventional mechano-thermal energy conversion mechanisms. We establish an equivalent acoustic impedance model to provide theoretical analysis of the underlying sound absorption mechanisms, with a theoretical maximum mechano-electro-thermal coupling efficiency approaching 100% under optimal conditions. We design fibrous triboelectric composite foam materials accordingly and show their substantially boosted acoustic absorption performance experimentally, where the adoption of diverse triboelectric material pairs validates that a larger difference in material charge affinities intensifies the local triboelectric effect and results in higher acoustic absorbing performance.

Noise pollution is omnipresent in modern society, affecting both humans and wildlife. Extensive research evidence supports that apart from causing annoyance, prolonged exposure to excessive noise levels can lead to direct or delayed hearing damage that can result in temporary or permanent auditory loss. Excessive airborne noise disturbs sleep, elevates stress hormone levels, incites inflammation, and even increases the risk of cardiovascular diseases^{1,2}. World Health Organization (WHO) defines noise above 65 decibels (dB) as noise pollution. It is estimated that one in five Europeans is regularly exposed to noise levels at night considered significantly harmful to health^{3,4}. Hence, as WHO guidelines urge, it becomes imperative to explore noise-mitigating solutions for unwanted anthropogenic noise to prolong healthy life years⁵.

Noise mitigation involves converting the mechanical energy carried by sound into alternative forms. In this regard, passive noise absorbers are much more realistic in practical implementations over their active counterparts due to their numerous advantages, including cost-effectiveness, streamlined design, minimal maintenance requirements, and the absence of power consumption or supporting systems⁶. Passive noise absorbers can be broadly grouped into two primary classes as porous absorbers and resonant devices. Exploiting resonance to design the sound absorption at certain frequency ranges, such as Helmholtz resonators^{7–9}, generally involves complicated design, complex structure, and narrow working bandwidth typically around certain high frequencies¹⁰, which has hindered their large-scale applications. Combining several resonant

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components aiming at broadband absorption may introduce unexpected interplay among the local resonances and lead to anti-resonances, which might cause rapid impedance oscillation and result in absorption dips¹¹.

In contrast, porous acoustic absorbers take in airborne sound waves by damping the oscillation of the air molecules to reduce echoes and vibrations. The network of interconnected pores generates various viscous, interfacial frictional, and structural damping effects to convert mechanical energy into thermal energy^{12–15}. However, passive airborne absorption is typically ineffective if the material is too thin compared to the wavelength, and thus this hinders their performances in the low-frequency range. Relying solely on porous absorbers for sound absorption, as shown in our calculations (Supplementary Note 1), is impractical for achieving adequate absorption, since the absorber thickness exceeds half a meter to match wavelengths of low-frequency sound. This well-known long-lasting challenge prompts the necessity to find more effective solutions.

The triboelectric effect, as a mechano-electro transformation mechanism coupling contact electrification and electrostatic induction^{16–19}, has been extensively explored for harvesting mechanical energy, including acoustic energy^{20–25}. However, it has not yet been connected with the local energy dissipation mechanism and further explored as a mechanism for sound absorption. Previous works from our group^{26–31} validate the feasibility of utilizing the piezoelectric effect for converting mechanical energy into electricity and thus enhancing sound absorption. Since it is evident that the triboelectric effect is significantly more effective for mechano-electro transformation at a lower frequency range below kilohertz^{32–34}, we believe appropriate utilization of the triboelectric effect has greater potential in realizing effective absorption of broadband low-frequency noise.

It should be noted that one main difference between acoustic energy harvesting and noise mitigation with triboelectric effect is that the former requires the collection of electrical energy with an external circuit system through the electrode, wire connection, and load while the latter involves in situ generation and dissipation of the electricity within the materials locally. The efficiency of acoustic energy dissipation is not limited by the lower energy coupling and higher loss due to impedance mismatching and electrical leakage in harvesting systems^{35,36}. Instead, its potential efficiency in acoustic energy dissipation could be close to the theoretical maximum efficiency of 100% for triboelectric mechanism, as previously reported^{37–42}, because no complex electrical charge collection, storage, and transmissions are required.

In this work, we propose a strategy for realizing airborne sound absorption through mechano-electro-thermal energy conversion by triboelectric mechanism and demonstrate improved sound absorption performance in porous fibrous composites by incorporating localized triboelectric effect and in situ electrical dissipation. An equivalent acoustic impedance model is derived through theoretical analysis with mechanical-acoustical analogy for validating the sound absorption attributed to the triboelectric effect in the porous fibrous composite foams, as confirmed by empirical results. With dedicatedly designed fibrous polypropylene (PP)/polyethylene terephthalate (PET) composite foam, a high noise reduction coefficient (NRC) of 0.66 is achieved, with an enhancement of 24.5% in sound absorption performance over foam without triboelectric effect. The concept is further validated with various material combinations, including PP/polyvinylidene fluoride (PVDF), glass wool (GW)/PVDF, and polyurethane (PU)/PVDF with diverse charge affinities and different triboelectric effects, with NRCs of 0.67, 0.71, and 0.79, respectively, corresponding to 22.6, 50.6, and 43.6% improvements. The outstanding sound absorption performances of more than 0.8 from 800 Hz and -1.00 above 1.4 kHz in the audible range over commercially available counterparts are demonstrated.

Results and discussion

Strategy of airborne sound absorption via triboelectric effect

To mitigate low-frequency environmental noises, acoustic waves with frequencies below 1600 Hz (corresponding wavelength above 216 mm, in room temperature of 25 °C, normal air pressure, Supplementary Note 1) are considered in this work as the targeted frequency range. Figure 1a illustrates the proposed mechanism of airborne sound absorption in a porous fiber-based triboelectric composite (TEC) foam that incorporates two distinct fiber materials along with electrically conductive elements (ECEs). The effective mixing of these two fibers, securely embedding the ECEs within the fibers, and filling the interstitial spaces ensures their continuous contact during mechanical vibrations induced by sound waves. Thus, the arrangement not only maximizes the contact area between the two different fiber materials but also enhances overall effective contact throughout the entire structure. One criterion for selecting the two fiber materials is their distinct charge affinities. An appropriate triboelectric material pair ensures the generation and accumulation of sufficient charges when an incident acoustic wave induces relative mechanical movement and contact electrification between two neighboring fibers.

For sufficient triboelectric charge generation, a high electron affinity difference is preferred between a positive triboelectric material that tends to lose electrons with its weaker affinity for negative charges, and a negative triboelectric material that tends to gain electrons with its stronger affinity for negative charges. After the positive and negative triboelectric materials contact and are separated, their surfaces will be positively and negatively charged, respectively. In this work, we selected multiple pairs of triboelectric materials with various electron affinity differences, including PP/PET, PP/PVDF, GW/PVDF, and PU/PVDF. The overall sound-absorbing performance of the fibrous TEC foam can be attributed to a synergy between its mechanical structural characteristics and the triboelectric effect between these two materials, as illustrated in Fig. 1b. Within this construct, we postulate the prototypical local triboelectric energy dissipator, as depicted in Fig. 1c. Wherein, the excitation from the airborne acoustic wave causes mechanical vibrations with relative movement between the fibers leading to contact electrification which can generate charges through the triboelectric effect. The accumulated charges are subsequently dissipated as heat through electro-thermal conversion via local circuits formed by conductive elements, as presented in Fig. 1d.

Local triboelectric generator sites and charge-dissipating paths

ECE concentration shows a deterministic impact on sound absorption since it determines the density of local triboelectric energy dissipator sites. A higher ECE concentration leads to the formation of more local triboelectric energy dissipator sites. It is worth noting that a threshold limit exists because an excessive increase in the ECE concentration may result in blocked pores inside the porous fibrous structure and substantially change the structure and property, such as porosity and tortuosity of the foam. As illustrated in Fig. 2a, any two intersecting adjacent fibers with an overlapped projection area S , is subject to local triboelectric effect. The distribution of the intersection angle β is established through Mont Carlo simulation (Fig. 2b), revealing a Gaussian distribution with a central value of β at 90 degree (Supplementary Note 2). This suggests that regardless of the specific angle, it is reasonable to assume the formation of the triboelectric energy dissipator remains viable, and the scenario remains valid. The subsequent analysis is developed within the framework of such deterministic unit, i.e., one triboelectric energy dissipator site comprising a pair of the negative and positive triboelectric fibers with adjacent ECE, as schematically illustrated in Fig. 2c. This unit is postulated as the smallest identifiable deterministic unit through which the entire composite structure can be regarded as a repetitive arrangement. Within this configuration, a pair of adjacent PET and PP fibers (as an example of the negative and positive triboelectric pair), capable of forming a

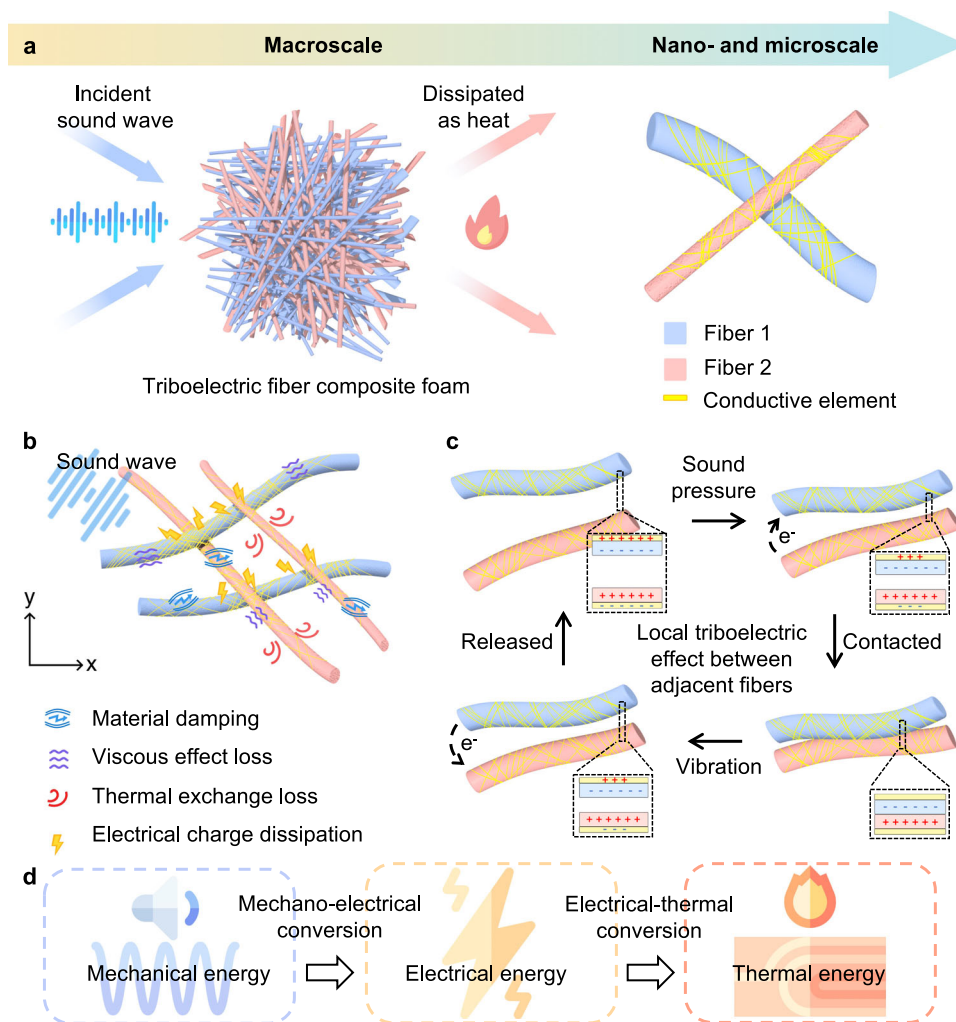


Fig. 1 | Airborne sound-absorbing mechanism with triboelectric effect introduced in the porous fibrous triboelectric composite (TEC) foam absorber.

a Schematics representation of the fibrous TEC foam absorber, with a detailed zoom-in illustrating two intersecting fibers (Fiber 1 and Fiber 2). Interaction between these fibers is activated by incoming acoustic waves, inducing relative movements among fibers, and initiating the triboelectric effect within their overlapping contact region. Fiber 1 and Fiber 2 represent a complementary pair of positive and negative triboelectric materials, respectively. The triboelectric charges generated during this interaction are dissipated through conductive elements and

eventually transformed into heat. **b** Schematic illustration of the sound absorption mechanisms of the fibrous TEC foam. **c** Contact electrification and electrostatic induction between the two fibers, prompted by the relative movement of adjacent fibers. **d** An overview of the mechano-electro-thermal conversion in fibrous TEC foam for sound absorption, emphasizing the energy conversion perspective: mechanical energy of sound waves undergoes transformation into electrical energy via the triboelectric effect, the charges are subsequently dissipated, culminating in the completion of electro-thermal conversion chain and facilitating effective noise attenuation.

triboelectric pair, are separated by a distance denoted as d , over which electrostatic charge Q and corresponding potential V are generated with the relative movements introduced by sound waves, as derived in Supplementary Note 2.

Local acoustic impedance model in fibrous composite foam

To investigate the impact of the triboelectric effect on the sound absorption behavior of porous absorbers, we establish a mechano-electro-thermal analysis model grounded on equivalent impedance in analogy with transducer equivalent circuits^{43,44}.

For understanding the acoustic impedance for the fibrous composite foam system, an area of interest is defined within the fibrous foam with a minimized differentiable local impedance. In this defined region, we consider a certain volume of air molecules situated between two adjacent fibers, which acts as a compressible fluid with mass M_m and characterized by a thickness equal to the perpendicular distance between the two fibers. Importantly, the thickness considered here is significantly smaller than the wavelengths of considered low-

frequency sound (Supplementary Note 1). The volume is also considerably smaller than the total volume of the fibrous foam, given the negligible amplitude of the fiber diameter in comparison with the scale of the entire fibrous foam. Within this focused region of air, the behavior of air molecules can be approximated as uniform. As sound waves propagate through this region, the behavior of the volumed air can be assimilated as the mechanical response of an object subjected to continuous compression by the sound pressure, the elastic force from the surrounding air within the fibrous structure, and resistive friction with the foam skeleton which impedes its compression. Considering these forces applied on the bulk air as an external force $F_{external}$, elastic force F_k , and resistive force F_r , respectively, the motion equation can be expressed accordingly (Supplementary Note 3).

A standard form of acoustic impedance can be expressed as $Z_a = R_a + j(\omega M_a - \frac{1}{\omega C_a})$, where R_a , ω , M_a , and C_a represent acoustic resistance, angular frequency, acoustic mass, and acoustic capacitance respectively. This implies that as the property of the material, acoustic

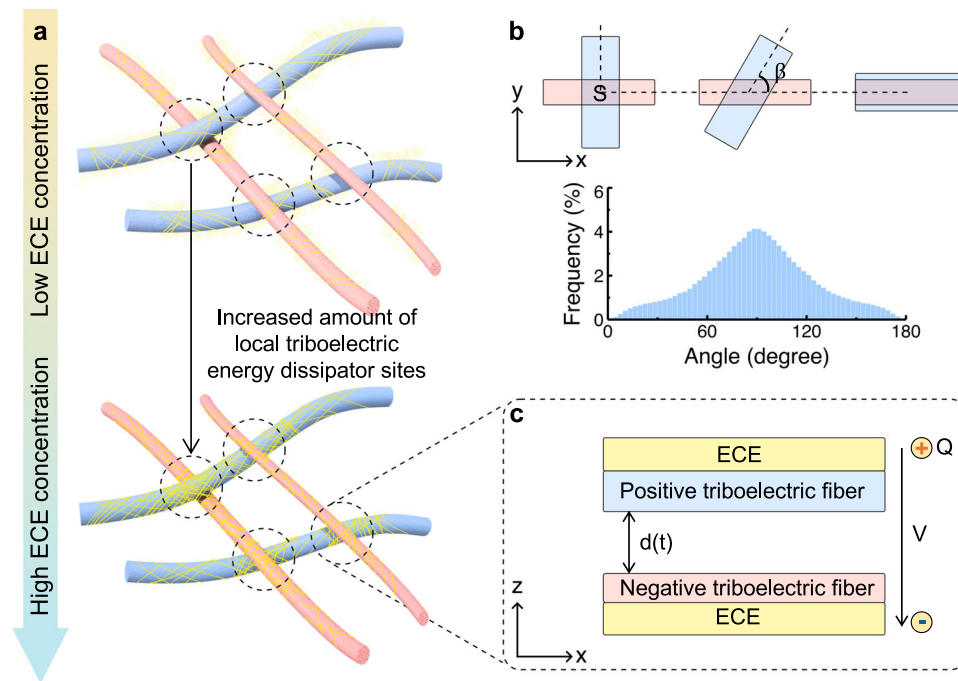


Fig. 2 | Working principle and design of fibrous composite foams showcasing increased electrically conductive element (ECE) concentration and localized triboelectric energy dissipator sites. a Increased ECE weight ratio leads to an increased number of local triboelectric energy dissipator sites and contributes to the sound absorption performance. **b** Geometric representation of adjacent fibers

with a projected overlapping area S and intersecting angle β . Probability distribution of β from the Monte Carlo simulation, showing a Gaussian distribution $\beta \sim (\frac{\pi}{2}, 33.6)$. **c** A single triboelectric energy dissipator unit between adjacent fibers formed by ECE-connected charge-dissipating pathways.

impedance measures the resistance to the flow of sound energy through the material by calculating the ratio of acoustic pressure to the associated particle speed with a spatial consideration in the foam. When the foam consists of a single material, there is usually no potential variation in triboelectric affinity within the foam. This analysis is also applicable to the scenario where the fibrous foam comprises of two or more types of materials with differing charge affinities. When triboelectric energy dissipators are present, continuous vibration of the fiber-based composite foam responds to incoming sound and absorbs the introduced acoustic energy. This gives rise to a continuous contact-and-detach cycle between the adjacent fibers, leading to contact electrification and the accumulation of static charge through the triboelectric effect. Note that initiating the triboelectric effect necessitates the following conditions: charge affinity difference between the materials and their relative movement. Additionally, a conductive element must be involved to discharge and dissipate the electrical energy. An equivalent acoustic impedance model after taking into account the nonnegligible electrostatic charges generated from triboelectric effect is derived (Supplementary Note 4), where the equivalent acoustic capacitance and acoustic resistance are changed due to the introduction of triboelectric effect. Specifically, for equivalent acoustic capacitance C'_a , new terms d , S , Q and V (Supplementary Note 2) are related to describing the local triboelectric generators; for equivalent acoustic resistance R'_a , it reflects the local dissipator for consuming the electric energy through Joule heat by the ECEs.

As a result, the overall equivalent acoustic impedance can be expressed as

$$Z'_a = R'_a + j \left(\omega M_a - \frac{1}{\omega C'_a} \right) \quad (1)$$

where equivalent acoustic resistance R'_a and equivalent acoustic capacitance C'_a are:

$$C'_a = C'_m S^2 = \frac{2C_m d^2 S^2}{2d^2 + C_m QV} \quad (2)$$

$$R'_a = \frac{R'_m}{S^2} = \frac{1}{S^2} \left(\frac{1}{2} \rho v C_d A + \frac{l^2 R}{v^2} \right) \quad (3)$$

Discussion on the local equivalent acoustic impedance model

Upon consideration of the physical interpretation of each component within the acoustic impedance formula, the equivalent acoustic mass can be regarded as constant irrespective of the presence or absence of the triboelectric effect, while the generation of electrostatic charges and local electric forces on the fibers lead to alteration of acoustic capacitance and acoustic resistance. The contact-detach behavior can be modulated by the frequency and intensity of the incoming sound. At the frequencies where the fibers undergo more pronounced relative movements, such as due to the local resonance of individual fibers, a greater amount of triboelectric charges is generated. It should be noted that V is limited by the air breakdown voltage over the gaps between the two triboelectric materials^{16,38} determined by air pressure and d (Supplementary Note 2).

Acoustic capacitance reflects the acoustic wave-absorbing capacity of the TEC foam. From the derived equivalent acoustic capacitance in Eq. 2, it is firstly noticed that when Q or V equals zero, the equivalent acoustic capacitance C'_a equates to the acoustic capacitance ($C_m = C'_m$, $C_a = C'_a$). This signifies that in the absence of static charges generated by the triboelectric effect, the TEC foam behaves in the same manner as acousto-mechanical terms in the general model. Secondly, when Q and/or d take on non-zero values, change in C_m conforms to a hyperbolic function. When there is a significant relative movement of

adjacent fibers introduced by sound, i.e., $\partial d/\partial t \gg 0$, a decrease in d results in a more abrupt change in C'_a . Conversely, very slight vibration, i.e., $\partial d/\partial t \approx 0$, leads to a very small value of Q and V generated (Equation S2.5) and consequently a minimal change in C'_a . From Supplementary Note 2, two fiber materials that have severe differences in triboelectric charge affinity will result in a greater amount of generated charge (higher absolute value of Q) and hence a greater V . It is speculated that at the resonance frequency of intersecting fibers, the magnitude of movement is maximized, contributing to a more intense change in d . With natural frequencies of PET/PP composite fibers estimated (Supplementary Note 5 and Supplementary Tables 1, 2), boosted vibration amplitude at resonance frequencies of fibers can be expected at around 428.5, and 971.2 to 1528.4 Hz range, which ultimately results in a higher acoustic capacitance. Note that real-world scenarios encompass a resonance frequency range within this interval, given the composite nature of fiber morphology representing a blend of these specified limits. This implies that the fiber composite structure can accommodate more sound waves with improved sound absorption performance around the low-frequency range.

Secondly, electrical energy carried by the electrostatic charges should be dissipated into heat through the local electric circuits to sustain the continuous energy conversion and loss. The alteration in acoustic resistance signifies the change in damping, or the ability to dissipate incoming acoustic energy. Apparently, from Eq. (3), R'_a is consistently greater than R_a and can be explained by two responsible factors: the addition of ECE increases the local tortuosity despite showing a minimal effect on the general tortuosity of the structure, introducing larger viscous loss as air molecules encounter increased drag forces; in addition, the formation of charge dissipation paths by ECE facilitates the Joule loss of electrical energy converted from acoustic energy via mechano-electrical conversion through the triboelectric effect. The enhancements in energy dissipation make the composite structure capable of absorbing more acoustic energy. Electromechanical coupling coefficient k^2 of such triboelectric effect enabled porous sound absorbers can be defined in analogy with electromechanical transducers^{45,46}, boundary conditions and limitations are discussed in Supplementary Note 6. Theoretically, the maximum mechano-electro-thermal coupling efficiency of the triboelectric effect can reach 100% (Supplementary Fig. 1) when without air breakdown voltage limitation under optimal structural and material parameters^{16,38,39}. For example, suppose material combination of PU and Polytetrafluoroethylene (PTFE) is selected, the upper limit of k^2 for such triboelectric energy dissipator can reach 0.72 at 700 Hz, with distance of 50 μm between the PU and PTFE fibers, and 0.86 at 1600 Hz.

Experimental demonstration of triboelectric effect boosted sound absorption

To experimentally verify the contribution of the triboelectric effect to the sound absorption performance of TEC foams, the concentration of ECEs is tuned to control the number of local triboelectric dissipator sites formed. Fibrous PP/PET foams were initially selected for proof of concept. Micro-CT scan (Fig. 3a) and SEM image (Fig. 3b) of a cubic section cut from the central part of the porous foam show effective PP/PET mixing. Silver nanowires, used as ECEs, are uniformly distributed (Fig. 3c and Supplementary Fig. 2), creating local charge dissipation pathways. With increasing ECE concentrations, both the dielectric constant and loss of the foam are boosted (Fig. 3d, e). When sound waves induce vibration and the associated electrical responses in the material, the increased dielectric loss can enhance the material's ability of electrical energy dissipation into heat, thereby the ability to absorb sound^{47,48}. The dielectric constant plateaus after reaching the percolation threshold at ~7 wt%. This marks the transition of the initially insulating foam to a conductive state³¹. Beyond this threshold, a conductive network forms, ensuring connectivity among conductive

elements within the 3D structure. The electrical conductivity of TEC foams is highly tunable, where it increases dramatically by five orders of magnitude from 10^{-6} to $10^{-1} \text{ S cm}^{-1}$, with ECE concentration rises from 0 to 45 wt% (Fig. 3f).

Note that the introduction of ECE is carefully managed to minimize the effect on the overall structure of the fibrous foam, with the sample porosities determined according to ASTM C830⁴⁹. Structural porosity is calculated by $\phi = 1 - \rho/\rho_f$, where ρ is the bulk density of the fibrous foam and ρ_f is the averaged fiber density (see Supplementary Table 1). The results, shown in Fig. 3g, align with the commonly accepted assumption that fibrous materials exhibit near-unity porosity⁵⁰.

Sound absorption coefficient α of these PP/PET/ECE TEC foams with a constant thickness of 20 mm and varying ECE concentrations were measured across the low-frequency range of 300–1600 Hz (Supplementary Fig. 3 and Supplementary Note 7). Here, α is independent of sound pressure level since they reflect the ratio of sound energy absorbed with respect to the total incident energy (Supplementary Fig. 4). A pronounced improvement in sound absorption performance with the introduction of an adequate amount of ECEs in the samples is shown (Fig. 3h). The pristine fibrous foam, devoid of ECEs, shows a sound absorption coefficient α of 0.80 at 1600 Hz. With higher ECE concentrations at 2, 3, 5, and 6 wt%, the sound absorption performance demonstrates a substantial enhancement, resulting in α values of 0.88, 0.95, 0.98, and 0.99 at 1600 Hz, indicating enhancement of 10.9, 20.5, 23.4, and 24.5%, respectively. This enhancement is particularly noteworthy since absorbing low-frequency sound with passive absorbers is generally a challenging task. Interestingly, α exhibits no further increase as the ECE concentration continues to rise beyond a saturation threshold of ECE concentration of around 6% (Fig. 3i and Supplementary Fig. 5a). For the TEC foams with high ECE concentration of 7, 8, 17, 20, and 40 wt%, their maximum α are 0.95, 0.95, 0.93, 0.92, and 0.92 with enhancement of 19.6, 20.9, 17.2, and 15.6%, respectively. The sound-absorbing performance curves display a consistent saturation with ECE concentration extending from 7 to 40 wt%.

The sound absorption behavior demonstrates a clear frequency-dependence. At higher sound frequencies, the porous foam exhibits an elevated value of α , indicating increased absorption of incident sound waves. Figure 3j, k shows the regression lines illustrating the enhancement in α resulting from the introduction of ECEs. In lower frequency ranges such as 600 and 800 Hz, the influence of an increased number of local triboelectric energy dissipator sites is relatively modest, with α increasing only slightly as the ECE concentration rises. However, when the sound frequency reaches around 1200 Hz, a remarkable improvement in sound absorption performance is observed with higher ECE concentrations. The enhancement in sound absorption reaches a peak at 1170 Hz, where the increment in ECE concentration has the most significant impact on sound absorption performance (Fig. 3l). The critical frequency range was carefully chosen and delimited to the frequency band of 1120–1290 Hz. Within this specific frequency range, the normalized enhancement factor exceeds 2.5, indicating a significant impact. This frequency range aligns with the theoretical analysis where a natural frequency range of 428.5 to 1528.4 Hz, as discussed in Supplementary Note 5. The enhancement may be attributed to the peak intensity of the triboelectric effect within the fibrous TEC foam in this particular frequency range, which has been verified with a high-speed camera observing the relative movements of adjacent fibers (Supplementary Movie 1).

Furthermore, we have observed that the frequency-dependent behavior is also intertwined with the ECE concentration, i.e., the number of local triboelectric effect sites. Figure 3m shows the noise reduction coefficient (NRC) of TEC foams with respect to their conductivity. NRC was calculated by averaging the sound absorption coefficient α at broad low-frequency range of 250, 500, 1000, and 1500 Hz, calculated by $\text{NRC} = \frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{1500}}{4}$, which exhibits sound

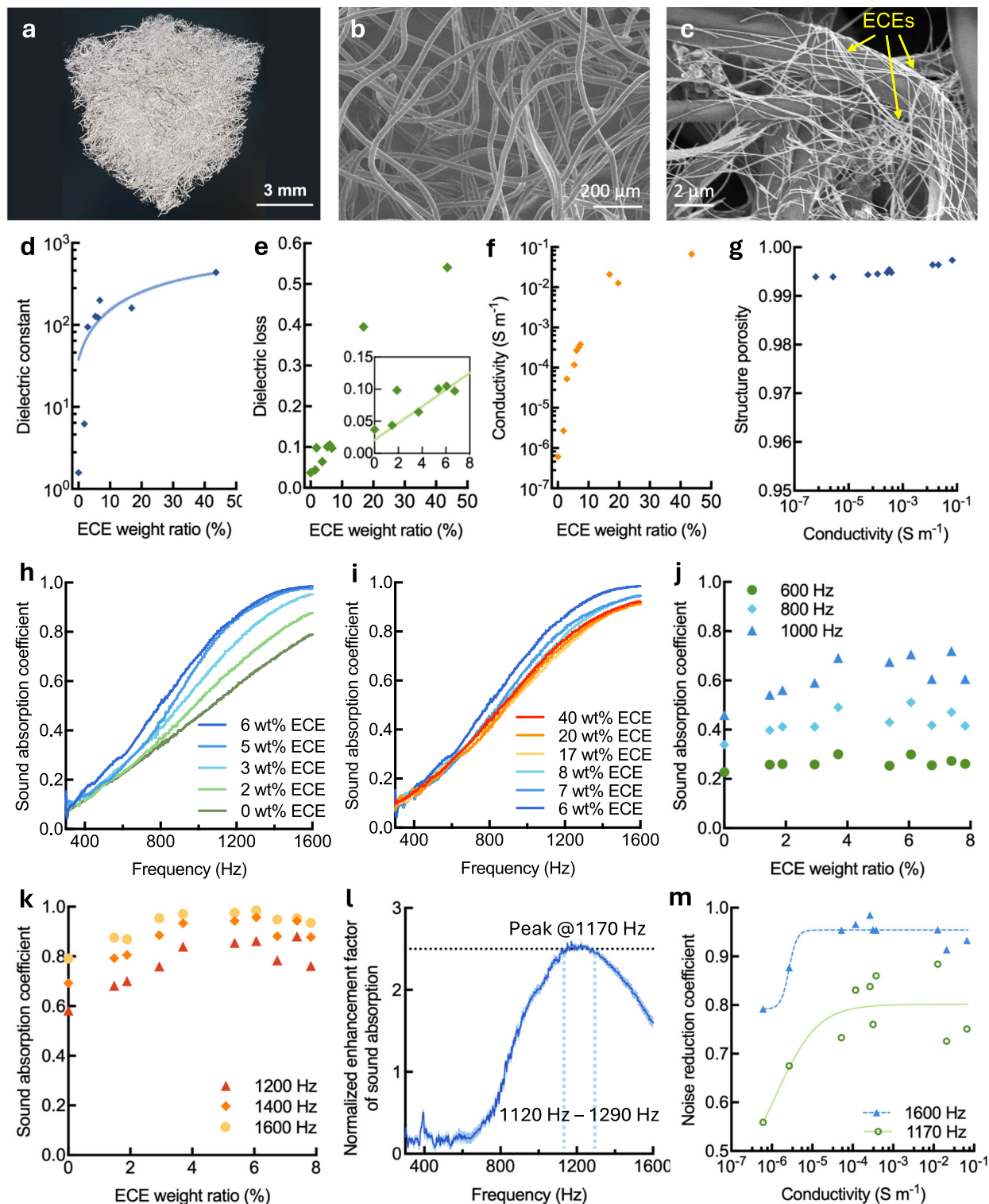


Fig. 3 | Tunable electrical and sound absorption properties of the PP/PET/ECE TEC foam. All samples are with thickness of 20 mm. **a** Isometric view of the cubic section from the central part of the fibrous foam sample. SEM images of pristine fibrous foam (0 wt% ECE) in **(b, c)** TEC foam with ECE at percolation threshold that forms local conductive paths. **d** Effect of ECE concentration on the dielectric constant of fibrous TEC foams with a corresponding polynomial fit curve $y = -0.07x^2 + 12.17x + 37.80$, $r^2 > 0.90$. **e** Effect of ECE concentration on the dielectric loss of fibrous TEC foams. The zoomed view shows the ECE weight ratio range within 8%, where the linear fit is $y = 0.013x + 0.021$, with a p value less than

0.01%. **f** Influence of ECE concentration on the conductivity of the fibrous TEC foams. **g** Modulating conductivity with ECE while preserving porosity with minimized change. **h, i** Influence of ECE concentration on the sound absorption performance of foams. Sound absorption enhancement at **j** lower frequency ranges and **k** higher frequency ranges, respectively. **l** Peak sound absorption enhancement at 1170 Hz due to triboelectric effect, significant enhancement from 1120–1290 Hz. **m** Noise reduction coefficient (NRC) in relation to conductivity follows a similar trend as the sound absorption coefficient. The fitted curves are hyperbolic, where for 1170 Hz is $y = \frac{0.784x}{2.648 \times 10^{-7} + x}$, and for 1600 Hz the fit is $y = \frac{0.953x}{1.275 \times 10^{-7} + x}$.

absorption performance with a highly correlated trend. As shown in Supplementary Fig. 5b, there is a precipitous rise in the conductivity of the fibrous TEC foam, occurring at the ECE weight ratio range of ~5 to 8%. This suggests that within this range, ECEs within the TEC foam establish a greater number of conductive pathways, consequently forming more localized electrical energy dissipators. Overall NRC and noise reduction coefficient over triboelectric frequencies 1120–1290 Hz (NRCTF) of varying ECE concentrations is calculated and plotted to assess the overall sound absorption (Supplementary Fig. 5c, d). The maximum value of NRC is 0.66.

For NRCTF, the highest performance located around the ECE concentration threshold, attains a value of 0.86. Previous work from our group also validated the role that ECEs in piezoelectric composite play in charge dissipation⁵¹, contributing to the conversion of acoustic energy into electrical energy and hence facilitates the enhancement in sound absorption performance. In that work, numerical simulation of a hollow piezoelectric PVDF cylinder revealed that, in the absence of conductive elements to dissipate charges, the piezoelectric effect had no influence on sound absorption performance; in contrast, when the porous structure exhibits semi-conductive properties, the electric energy converted from sound wave vibration via the piezoelectric effect can be dissipated by conductive elements and consequently helps enhancing the sound absorption performance, although the frequency range in the previous analysis on the piezoelectric effect is relatively higher.

Further enhancement of sound absorption performance in various composites with triboelectric effect

The gist of improving sound absorption performance is to generate more electrostatic charges and the formation of more effective

electrical energy dissipation into heat. In this regard, it is favored to adopt triboelectric pairing materials possess big charge affinity difference. Additionally, one of the materials, either positive or negative, can be selected from a group of piezoelectric materials to acquire additional mechano-electrical energy conversion through combination of both local triboelectric and piezoelectric effects. Here, piezoelectric PVDF polymer is selected to form material pairs with hybrid piezoelectric and triboelectric effects, including PP/PVDF, GW/PVDF, and PU/PVDF, considering their variations in charge affinity differences.

As shown in Fig. 4a, when pairing with material with more negative charge affinity than PVDF, such as PP, PVDF serves as the positive triboelectric material, while with GW/PU with more positive charge affinity, PVDF serves as the negative triboelectric material. ECEs added to the composite foams are controlled to have a negligible impact on the structural properties to enable electrical discharge and formation of triboelectric energy dissipators, where silver is selected for PP/PVDF and conductive multi-walled carbon nanotubes (MWCNTs) for GW/PVDF and PU/PVDF. Surface morphologies of these TEC foams are shown in Supplementary Fig. 6. Their acoustic absorption performances are examined. NRCs of acoustic absorbers consisting of pristine PP/PVDF, GW/PVDF, and PU/PVDF fibers without ECEs are similar, with a value of 0.55, 0.47, and 0.55, respectively (Fig. 4b, c). Without ECEs forming conductive pathways to discharge, charge generation will soon reach saturation. In contrast, after triboelectric pairs and ECEs introduced, their NRCs for PP/PVDF/ECEs, GW/PVDF/ECEs, and PU/PVDF/ECEs increased to 0.67, 0.71, and 0.79, respectively. In addition, the material pairs with a wider gap on the triboelectric charge affinity, such as for GW/PVDF/MWCNTs and PU/PVDF/MWCNTs present more significant NRC enhancement due to the bigger

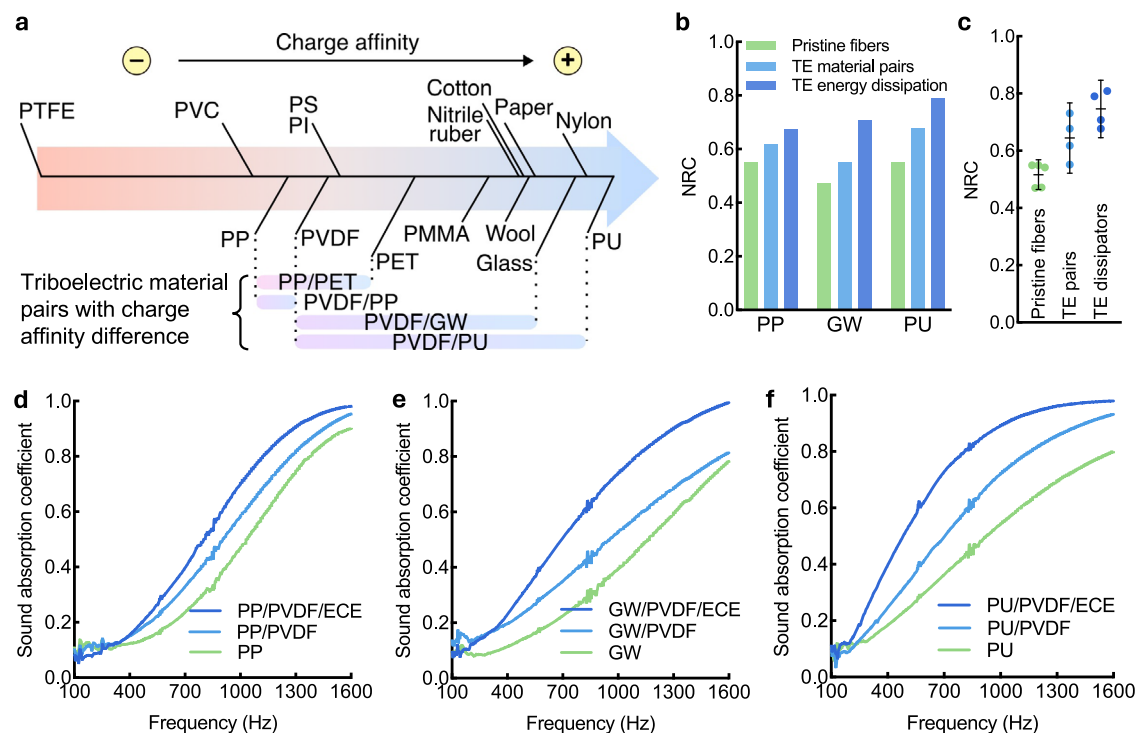


Fig. 4 | Extended experimental validation on triboelectric material pairs with varying charge affinity and their acoustic absorption coefficients. All samples are with thickness of 25 mm and a diameter of 100 mm. **a** Charge affinity series of common triboelectric materials. **b** Comparison of noise reduction coefficient (NRC) for TECs made of PP/PVDF, GW/PVDF, and PU/PVDF, with and without ECE, concentration of the conducting elements satisfies the percolation threshold at 5 wt.% in the final composite material. **c** Prominent improvement in NRC among

groups. The error bars represent standard deviations over at least three samples. Sound absorption coefficients of **d** TEC foams made of PP/PVDF/ECE forming triboelectric dissipators, in comparison with PP/PVDF and PP. **e** TEC foams made of GW/PVDF/ECE forming triboelectric dissipators, in comparison with GW/PVDF and GW. **f** TEC foams made of PU/PVDF/ECE forming triboelectric dissipators, in comparison with PU/PVDF and PU.

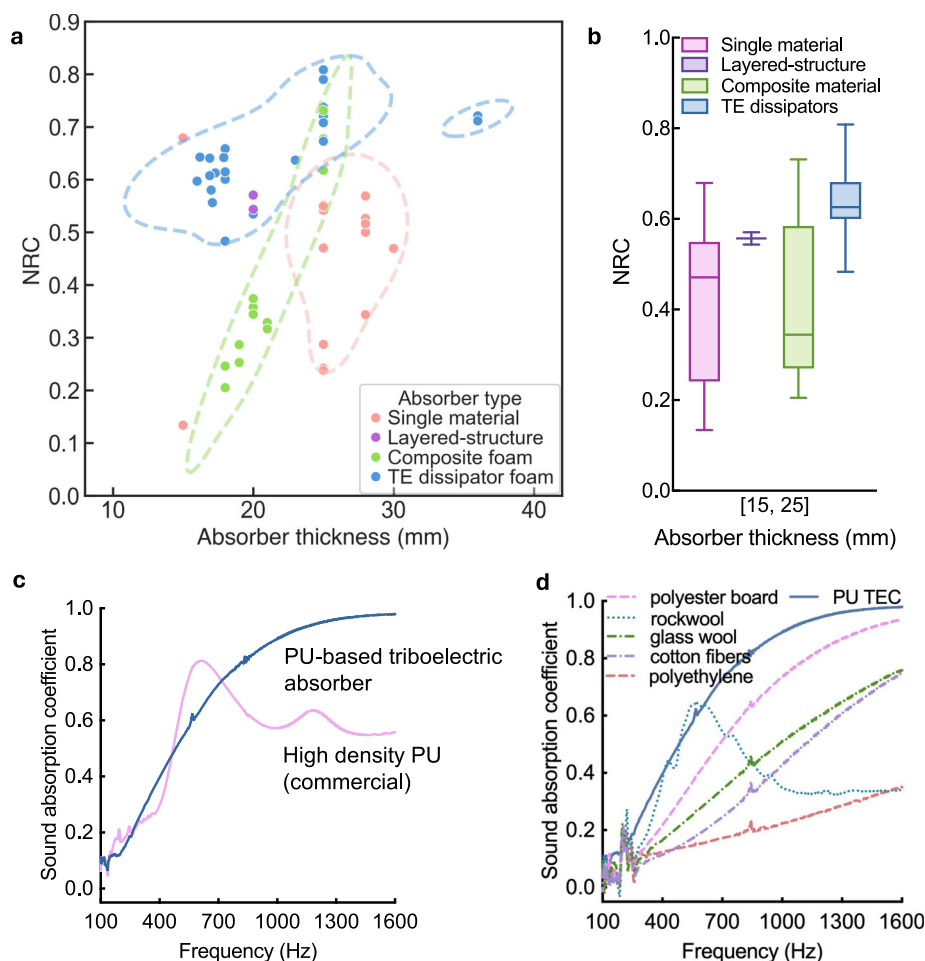


Fig. 5 | Outstanding sound absorption performance of the composite foam with triboelectric effects over common acoustic absorbing products.

a Distribution of NRC of acoustic absorbers with triboelectric effect. The dots represent NRC values of acoustic absorber samples with different types and varying absorber thickness. Despite the reduced thickness, triboelectric-enabled absorbers surpass acoustic absorbers made of single materials, composite materials, or

layered structures. **b** NRCs of acoustic absorbers with triboelectric effect outperform other groups without. **c** Sound absorption coefficient of PU-based TEC foam shows higher sound absorption over its commercial counterpart. **d** Superior performance of PU-based TEC foam in comparison with a variety of commonly used commercial products.

contribution from triboelectric effect in TEC foams (in reference to the gap marked in Fig. 4a) The improvements in NRC for PP/PVDF/ECEs, GW/PVDF/ECEs, and PU/PVDF/ECEs are 22.6, 50.6, and 43.6%, corresponding to the gap on the triboelectric charge affinity of 15, 100, and 115 nC J⁻¹, respectively (Supplementary Table 3). The acoustic absorption coefficients of these TEC foams are presented in Fig. 4d–f, among which PU/PVDF/ECE TEC foam performs the best: more than 0.50 from 450 Hz, and more than 0.80 from 800 Hz, and ~1.00 above 1.4 kHz, in the audible range.

Our results validate that selecting the pair of materials with maximized difference in their tendency to gain or lose electrons as provided from their electron affinity values plus adequate electrical conducting elements is an important guideline to design and obtain high-performance sound-absorbing materials.

Incorporating triboelectric energy conversion and dissipation effects into TEC foams yields acoustic absorption performances surpassing the commercially available counterparts. In Fig. 5a, the distribution of NRC values among various materials, including single materials, composite materials, or layered structures, reveals a trend in which the TEC foams exhibit higher NRC at relatively smaller thickness. Supplementary Table 4 provides the sample details. Sound absorbers employing triboelectric effect demonstrate notably higher NRC compared to those of single materials, layered structures, or composites

without triboelectric effect (Fig. 5b). As shown in Fig. 5c, the PU-based triboelectric absorber consistently outperforms its commercial high-density PU counterpart across a broad frequency range, despite its less dense structure. Furthermore, the PU/PVDF/ECE TEC foam, represented by the blue solid curve in Fig. 5d, surpasses a variety of commonly used commercial sound absorbers—including polyester board, rockwool, glass wool, cotton fibers, and polyethylene foam—in sound absorption across various frequencies.

In summary, we have proposed a strategy for airborne sound absorption by adopting synergistic local triboelectric and conducting effects for enabling effective mechano-electro-thermal conversion energy dissipation. The significant contribution of the triboelectric effect in achieving outstanding broadband low-frequency sound absorption performance has been demonstrated in porous fibrous composites comprising the paired materials with large electrical affinity difference, in contrast with the common commercial sound absorbers. We established an acoustic impedance model taking into account the influences of the local triboelectric energy conversion and dissipation on the effective acoustic capacitance and resistance. Both the theoretical analysis and experimental results revealed that selecting the pair of materials with maximized difference in their electron affinity values plus adequate electrical conducting elements is an important guideline to design and obtain high-performance sound-

absorbing materials. The performance improvement in sound absorption of the triboelectric fiber composites is found most prominent when the sound frequency range matches the resonance frequencies of the individual fibers in which their relative movements and, hence, the triboelectric effects are maximized. Without requiring complex electrical charge collection, storage, and transmissions resulting in the low efficiency in energy harvesting application, the application of triboelectric effect in acoustic absorption only involves local electrical energy dissipation, in which the theoretical maximum efficiency of 100% in optimal conditions could be possible.

Methods

Materials

The porous fibrous composite was prepared by multiple dip-coating cycles of the acoustic insulation trim (RS PRO, 881-4557) into different concentrations of diluted solutions of silver nanowires, as ECE introduced to the fabricated foam (Coldstones Technology, CST-NW-S35). The trims were cut and stacked to thick foams considering its inherent fluffy nature. The stacked trims were compressed with a hydraulic presser at 5 tons for 15 s before dip-coating in the solution. The composite foams were then dried in an oven at 60 °C to ensure the removal of the solution and even distribution of silver nanowires. The electrospinning technique was used to deposit PVDF or PVDF/MWCNT electrospun fibers on a porous GW sample. A polymer solution was prepared by dissolving 5 wt% PVDF in mixed DMF and acetone solvent (50:50 by volume) in a silicone oil bath at 60 °C. MWCNT with a concentration of 7 wt% (in the solid PVDF powder) was added to the polymer solution allowing the integration of the ECE with the fibers in a single-step fabrication process. A spinneret containing PVDF solution was used to deposit the PVDF electrospun fibers. The solution was injected from the spinneret needle at a flow rate of 0.5 mL h⁻¹ with a syringe pump (SP100IZ Syringe Pump, 789,100 W, USA). A high voltage power supply of 15 kV was applied with a distance of 10 cm from the tip of the spinneret containing PVDF solution and the grounded GW sample. A continuous fine jet of the polymer solution was ejected from the spinneret and moved through the electric field to be deposited on the grounded GW sample, which was flipped on all sides every 30 min to allow the fine PVDF electrospun fibers to diffuse inside its porosity and cover the whole surfaces. The PVDF electrospun fibers-coated glass wool was then annealed at 135 °C for 24 h. Yarns of PVDF, PMMA, PS, and Ag-coated nylon were purchased from Textile Development Associates, Inc. (USA). The yarns were woven into porous samples by a 22-needle weaving machine round knitting loom (Sentroknitting, SG).

Characterizations

Acoustic absorption performances of the fibrous composite foams were tested according to ASTM E1050-19 standard test method using a standard Bruel & Kjaer acoustic impedance tube (Supplementary Note 7). Surface morphology was examined using a FESEM (JSM-6700F, JEOL). The electrical properties of the samples were measured with an impedance analyzer (Agilent 4294A).

Data availability

All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Source data and code that supports the plots within this paper are available in the open repository link: <https://github.com/ginwithpepsi/Triboelectric-for-Sound-Absorption>. Source data are provided with this paper.

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Author contributions

K.Y. conceived the idea of this work. J.L. developed the theory. J.L., Y.M.Y., and P.C.L. designed and conducted the experiments. J.L. and Y.M.Y. performed characterizations. J.L., Y.M.Y., and K.Y. analyzed the results. J.L. prepared the manuscript, Y.M.Y. and K.Y. revised the manuscript. S.R. and K.Y. supervised the study. All authors reviewed and agreed on the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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