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REVIEW

Piezoelectric energy harvesters for railways: recent trends and future opportunities

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Abstract

A growing desire for the availability of clean energy in the railway environment has led to advancements in energy harvesting technologies. In particular, piezoelectric energy harvesters (PEHs) have been shown to have potential benefits for the railway industry. Thus, this paper provides a review of PEH solutions for railway energy harvesting, focusing on their design, optimization, and implementation. It examines various energy sources, including vibration, mechanical stress, friction, sound, and wind energy, while also discussing the structural designs and materials employed to improve their performance. The review highlights the potential applications of PEHs in powering self-sustaining wireless sensors, monitoring systems, and trackside electronics. Despite notable advancements, challenges persist, particularly in energy conversion efficiency, structural durability, data transmission, and the integration of interface circuits. The paper further explores potential future research directions, underscoring the need for more efficient energy harvesting systems, multi-mechanism coupling, and robust solutions for the harsh environmental conditions under which railways operate. If future research can address these challenges, PEHs hold promise for powering smart and sustainable railway infrastructure.

Keywords Ballasted railway track · Piezoelectric energy harvester · Mechanical energy · Sound and vibration · Friction · Wind

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Nomenclature

Serial Number	Symbol	Notation
1	ρ	Density (g/cm^3)
2	E	Young's modulus (GPa)
3	ε	Dielectric constant
4	d_{31}	Piezoelectric constant (pC/N)
5	d_{33}	Piezoelectric constant (pC/N)
6	Q	Mechanical quality factor
7	k_{31}	Electro-mechanical coupling factor
8	k_{33}	Electro-mechanical coupling factor

1 Introduction

Rail transportation has become an important mode of global transit due to its high capacity for passengers and freight, as well as its economic efficiency, and reliability (Lapidus et al. 2019). With the rapid expansion of railway networks, there has been a significant increase in train speed, passenger and freight volumes, and the overall network size. As a result, the health monitoring of the railway infrastructure

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has become increasingly crucial to ensure safe operations (Asada et al. 2013; Entezami et al. 2017; Li et al. 2019). Traditionally, railway condition monitoring was conducted manually, but manual inspections are challenging due to their high cost and issues with repeatability (Lin et al. 2018; Falamarzi et al. 2019; Di Natali et al. 2023) Railway operators now require the capability for long-term, long-distance monitoring to assess the condition of railway systems over extended periods, a task that is challenging to achieve with manual maintenance alone (He et al. 2019; Guo et al. 2023).

The advent of advanced sensors, data acquisition systems, and data processing technologies has facilitated the development of Structural Health Monitoring (SHM) in railways (Barke and Chiu 2005; Yüksel et al. 2018; Li et al. 2021b). Typically, these monitoring systems are either battery-operated or connected through intricate cabling systems, both of which present sustainability and maintenance challenges (Fu et al. 2021). Moreover, the adoption of wireless power transmission technologies, such as wireless charging via electromagnetic fields and microwave wireless power transmission, presents significant risks (Jawad et al. 2017; Asiful Huda et al. 2022). One challenge in implementing these technologies is ensuring the safety of railway operations. For example, magnets in electromagnetic fields can adhere to the rail, and microwave signals may interfere with other railway communication systems. In response, the integration of self-powered monitoring systems using ambient energy harvesting has gained considerable research attention. These systems claim to offer long-term, low-maintenance, real-time monitoring solutions (Min et al. 2023), enabling continuous sensor operation without the need for external power sources (Hosseinkhani et al. 2021; Salehi et al. 2021; Zuo et al. 2023).

In the railway environment, energy harvesting holds promise for powering self-sustaining monitoring systems (Bosso et al. 2021; Sun et al. 2025). Ambient energy from railway vehicles and tracks, such as vibration from trains, friction-induced vibrations during braking, wind-induced, and sound-induced during operation, are all potential sources for energy harvesting (Kralov et al. 2011; Iqbal et al. 2021; Qi et al. 2022; Zaiyu et al. 2023). Additionally, other ambient energy resources, such as mechanical energy from stress transfer, wheel-rail interactions, and rail irregularities, have also been explored (Díez et al. 2019; Pan et al. 2021). These forms of energy can be converted into electricity through various energy harvesting technologies, as shown in Fig. 1, providing a potential power solution for remote areas where inspection is challenging.

Recent advancements in energy harvesting technologies within the railway sector include piezoelectric, electromagnetic, electrostatic, and triboelectric mechanisms (Duarte and Ferreira 2017). In particular, piezoelectric energy harvesting offers an energy conversion mechanism that operates without the need for voltage sources, or contact with another material (Sezer and Koç 2021). Piezoelectric energy harvesters (PEHs) can potentially provide higher power density and voltage output, typically 3–5 times greater than other mechanisms (Guan et al. 2020). Their compact size also allows for integration into confined spaces (Sezer and Koç 2021; Shan et al. 2022a). In contrast, while solar panels can be reliable in certain weather conditions, they are often impractical for higher power applications due to the large panel sizes required (Hao et al. 2021, 2022). Note that the vibration frequencies in high-speed railways, which range from 15 to 650 Hz, suggest that PEHs need to operate over a broad frequency range without experiencing heavy load (Zhai et al. 2015).

Considering the potential advantages outlined above, this paper provides an investigation into the application of piezoelectric energy harvesters (PEHs) in the railway sector, with a focus on addressing critical challenges related to energy efficiency, conversion and durability. The novelty of this work lies in its exploration of various applications of PEHs, offering more effective solutions for capturing the broad range of vibration, mechanical, friction-induced, sound, and wind energies prevalent in railway environments. Furthermore, it highlights critical technologies, including the potential for powering sensors, the development of interface circuits, transmission and communication technologies and multi-mechanism harvesting. By addressing these challenges and proposing innovative strategies, the work contributes to the future development of more efficient, scalable, and durable PEHs for powering self-sustained monitoring systems in railway infrastructures.

2 Principles of piezoelectric energy harvester

2.1 Piezoelectric effect

The operational principle of the piezoelectric energy harvester is based on the polarization characteristics of piezoelectric materials (Naifar et al. 2017; Yang et al. 2018). To generate a potential difference between the poles of a piezoelectric sheet, a displacement or force must be applied to one end of the sheet, utilizing the direct piezoelectric effect. Conversely, the reverse piezoelectric effect occurs when a voltage is applied across the poles of the sheet, causing it to deform.

The voltage generated within a piezoelectric sheet via the direct piezoelectric effect is proportional to the displacement of the plate, as expressed by Eq. (1):

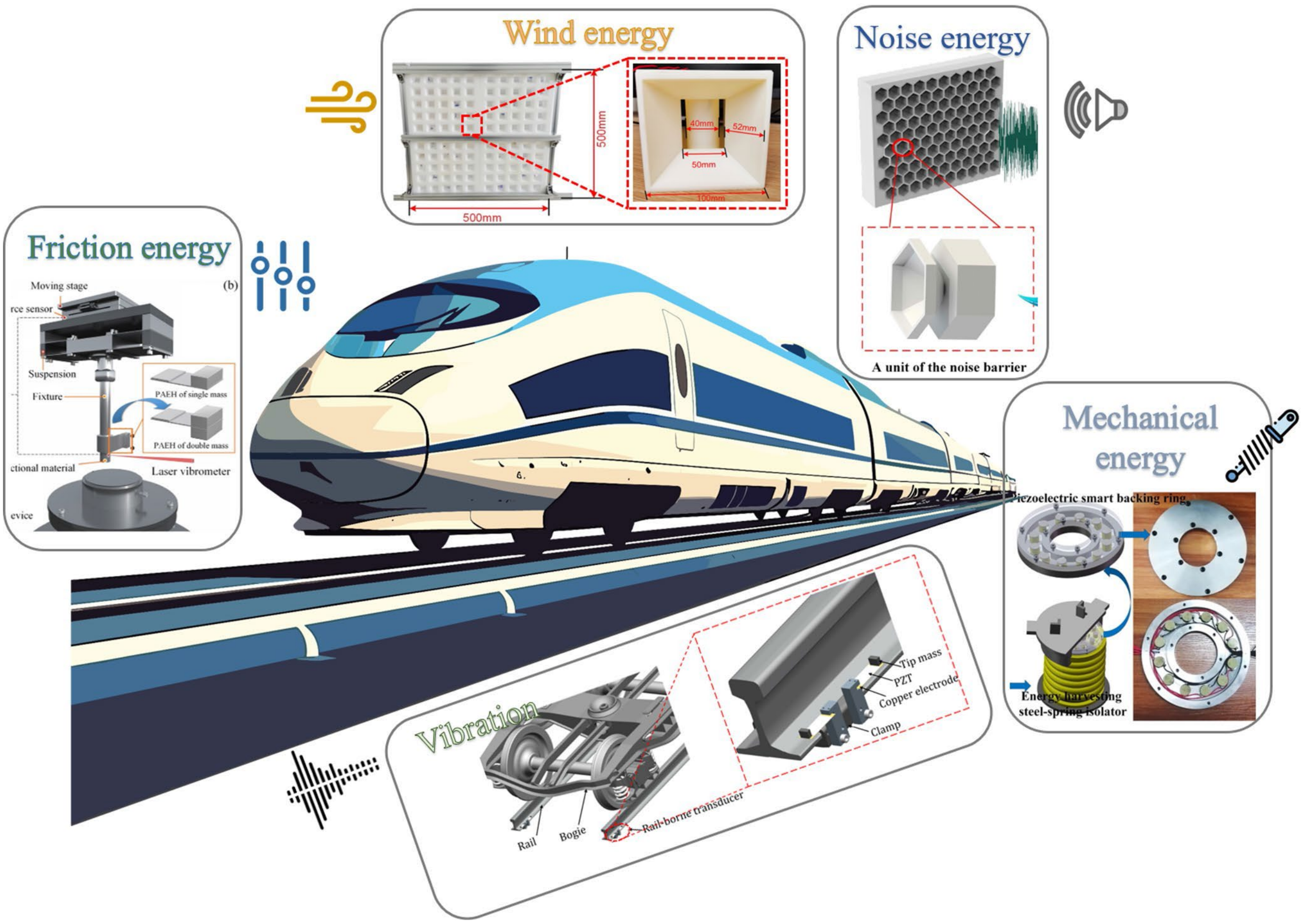

Fig. 1 Potential energy sources in railways

$$D_m = d_{mj}T_j$$

$$D_m = e_{mi}S_i \tag{1}$$

Where D_m is electric displacement, d_{mj} and e_{mj} are piezoelectric strain constant and piezoelectric stress constant, respectively, T_j and S_i are stress component and strain component, respectively (Toprak and Tigli 2014).

The piezoelectric sheet operating under the reverse piezoelectric effect is shown in Eq. (2):

$$S = d^T E$$

$$T = e^T E \tag{2}$$

Where d^T and e^T are the transposed matrices of the piezoelectric constants d and e.

2.2 Modes of operation

The piezoelectric effect stems from the electromechanical interaction between strain and electric fields. The intensity of this effect is influenced by the orientation of both the electric field and strain relative to the direction of polarization. Within piezoelectric materials polarized in the third direction, various operational modes are designated d_{ij}, in which j represents the applied strain component and i indicates the direction of the resultant electric field (Sharma et al. 2022). The common operational modes used in practical scenarios include d_{31} (transverse mode), d_{33} (longitudinal mode), and d_{15} (shear mode), as depicted schematically in Fig. 2(a)-(c). In the d_{31} mode, strain occurs along the first direction of the piezoelectric material, with polarization aligned in the third direction. This mode is characterized by significant deformation from the minimal force due to its perpendicular orientation relative to both the polarization and vibration directions. It is particularly advantageous for energy conversion from low-strain sources, though it results in lower output voltage and power (Lu et al. 2004). In contrast, the d_{33} mode, where both strain and polarization occur in the third direction, experiences less deformation because the applied force is aligned with the polarization direction. This alignment enables a higher electromechanical coupling coefficient, which can lead to greater voltage

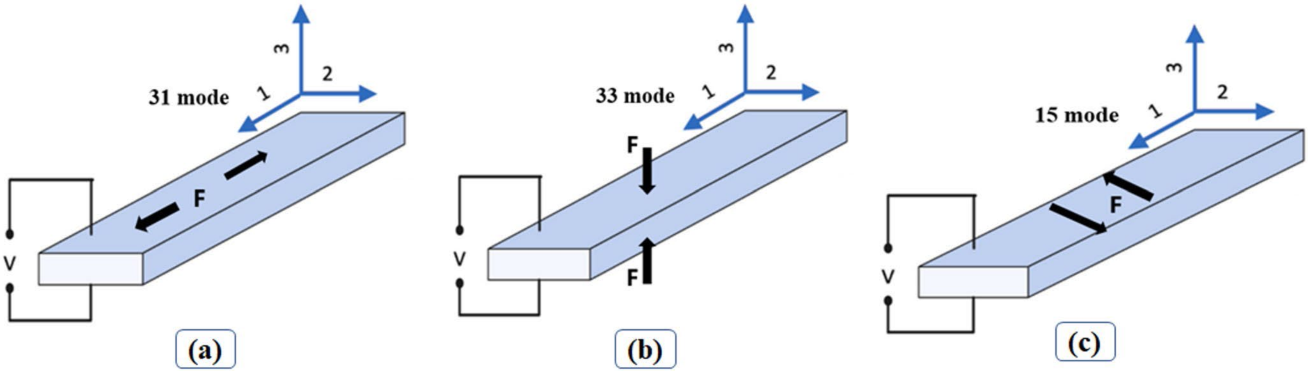

Fig. 2 Modes of operation: (**a**) d_{31} mode, (**b**) d_{33} mode, (**c**) d_{15} mode (Sharma et al. 2022)

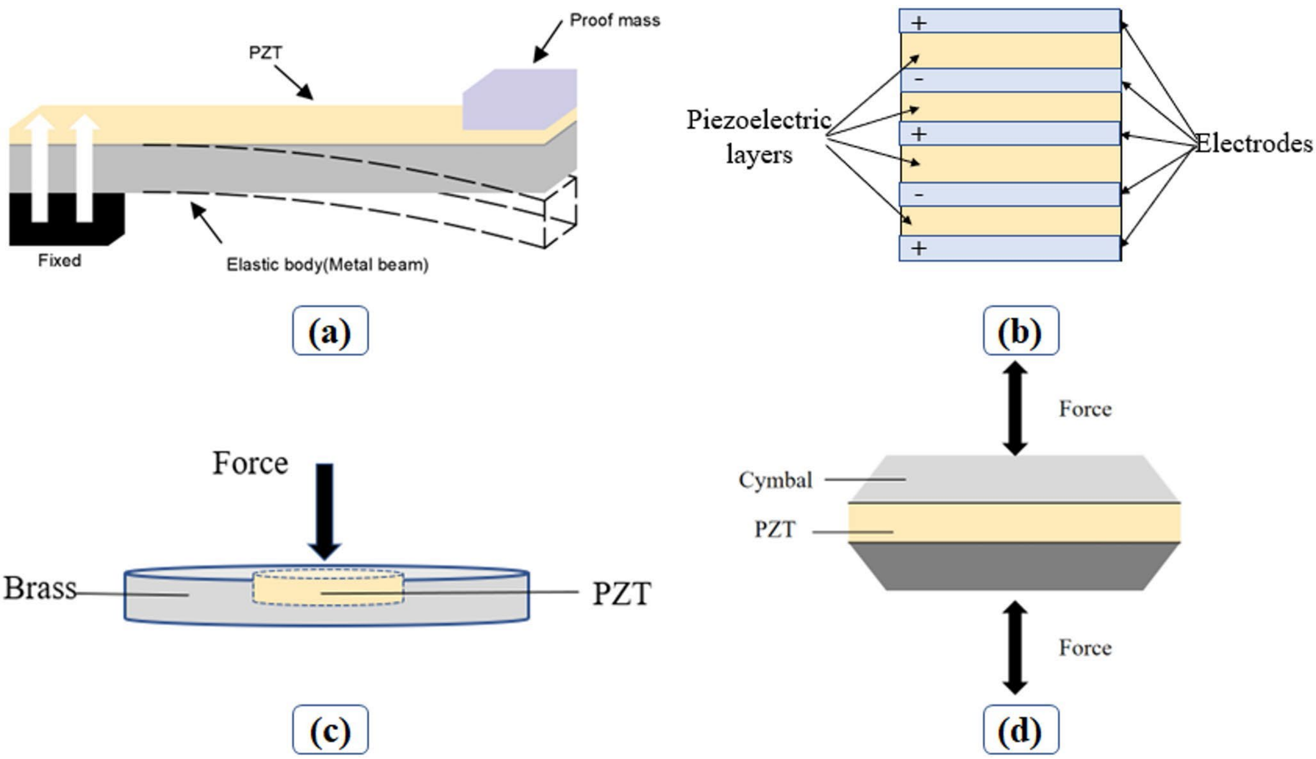

Fig. 3 Typical PEH structures: (**a**) cantilever, (**b**) stack, (**c**) cymbal, (**d**) diaphragm (Covaci and Gontean 2020)

output (Roundy et al. 2003). The d_{15} mode, in which strain and polarization are perpendicular, is rarely used because it tends to lose polarization (Gao et al. 2018).

2.3 PEH structures

2.3.1 Cantilever

Piezoelectric energy harvesters (PEHs) often employ a cantilever beam structure composed of lead zirconate titanate (PZT) to maximize power output. This design is driven by the increased force exerted on piezoelectric components during vibration, which significantly alters their shape (Kang et al. 2016; Liu et al. 2021). A typical cantilever beam PEH configuration is shown in Fig. 3(a). These PEHs generally feature a rectangular cantilever beam, where the piezoelectric sheet is subjected to linear bending stress along its length. The bending stress is highest at the fixed end and decreases toward the free end. This distribution can result in excessive strain and fatigue at the fixed end while underutilizing the piezoelectric materials at the free end.

To achieve a more uniform and extensive strain distribution, researchers have explored cantilever beams with various shapes beyond the conventional rectangular configuration (Roundy and Wright 2004; Kaur et al. 2016; Hu et al. 2022). These include triangular (Basari et al. 2014;

Muthalif and Nordin 2015; Zhang et al. 2019), conical (Xie et al. 2017; Keshmiri et al. 2018), L-shaped (Nie et al. 2019; Debnath and Kumar 2020), S-shaped (Liu et al. 2012; Shindo and Narita 2014), V-shaped (Jiang et al. 2021), and arc-shaped configurations (Yang et al. 2017b; Zhou et al. 2020), as shown in Fig. 4(a)-(f).

2.3.2 Stack

To optimize the use of the d_{33} d_{33} mode, a PEH design incorporating multiple stacked piezoelectric layers, which exhibits an enhanced electromechanical coupling coefficient, is illustrated in Fig. 3(b). Xu (Xu et al. 2013) reported a configuration consisting of 300 PZT layers, where the alternating polarization of each layer ensured that the electric field consistently pointed toward the same electrode. This stacked design improves both power generation and power density compared to traditional cantilever sheets. However, due to the inherently high stiffness of piezoelectric stacks, a significant compressive force is required, or the system must be integrated with a mechanical force amplifier to achieve optimal performance (Liu et al. 2018).

2.3.3 Cymbal

To capitalize on the advantages of piezoelectric stacks, research into the amplification effect of cymbal-type PEHs has been conducted to enhance harvesting performance. This configuration consists of PZT stacks clamped between metal end caps at the top and bottom, as shown in Fig. 3(c). Cymbal-type harvesters have gained popularity for energy harvesting applications in recent years due to their low frequency, compact size, large displacement, and high sensitivity. When a load is applied to the metal top of the harvester, the force is transferred to the piezoelectric plate, inducing polarization along its thickness. Figure 5(a)-(d) illustrates typical cymbal piezoelectric harvesters and their various applications.

2.3.4 Diaphragm

A specialized PEH disk structure, also known as a piezoelectric diaphragm structure, consists of electrodes welded to piezoelectric elements mounted on copper plates, as shown in Fig. 3(d). Deformation of the piezoelectric diaphragm, caused by stretching or compression due to extrusion, induces polarization proportional to the surface deformation, resulting in a potential difference along the thickness direction. The slim profile of the PEH diaphragm facilitates its integration into complex settings. Research has focused on developing piezoelectric thin diaphragm energy harvesters, exploring various configurations, including arrays, stacks, and individual diaphragms, as shown in Fig. 6(a)-(f).

2.4 PEH materials

Piezoelectric materials are substances that generate an electrical charge in response to applied mechanical stress. Based on their structural characteristics, these materials can be classified into four categories: single crystals, ceramics, polymers, and composite materials (Kumar and Srivastava 2022).

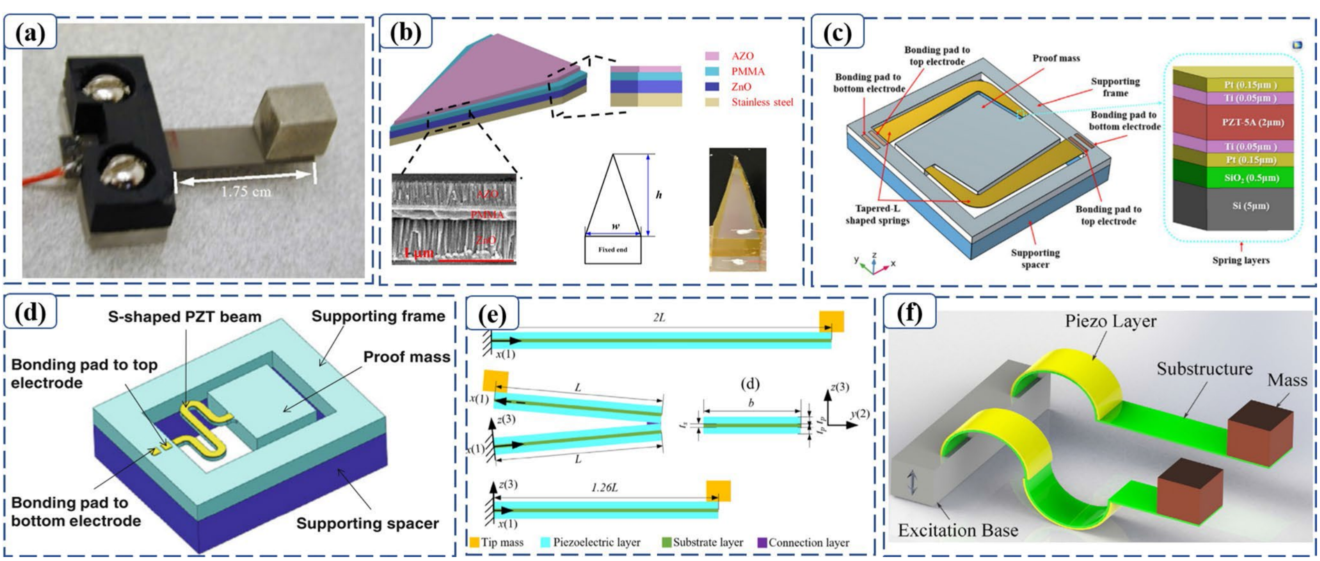

Fig. 4 Typical cantilever-type structures for PEH include (**a**) rectangular (Roundy and Wright 2004), (**b**) triangular (Zhang et al. 2019), (**c**) L-shaped (Debnath and Kumar 2020), (**d**) S-shaped (Liu et al. 2012), (**e**) V-shaped (Jiang et al. 2021), and (**f**) arc-shaped (Yang et al. 2017b)

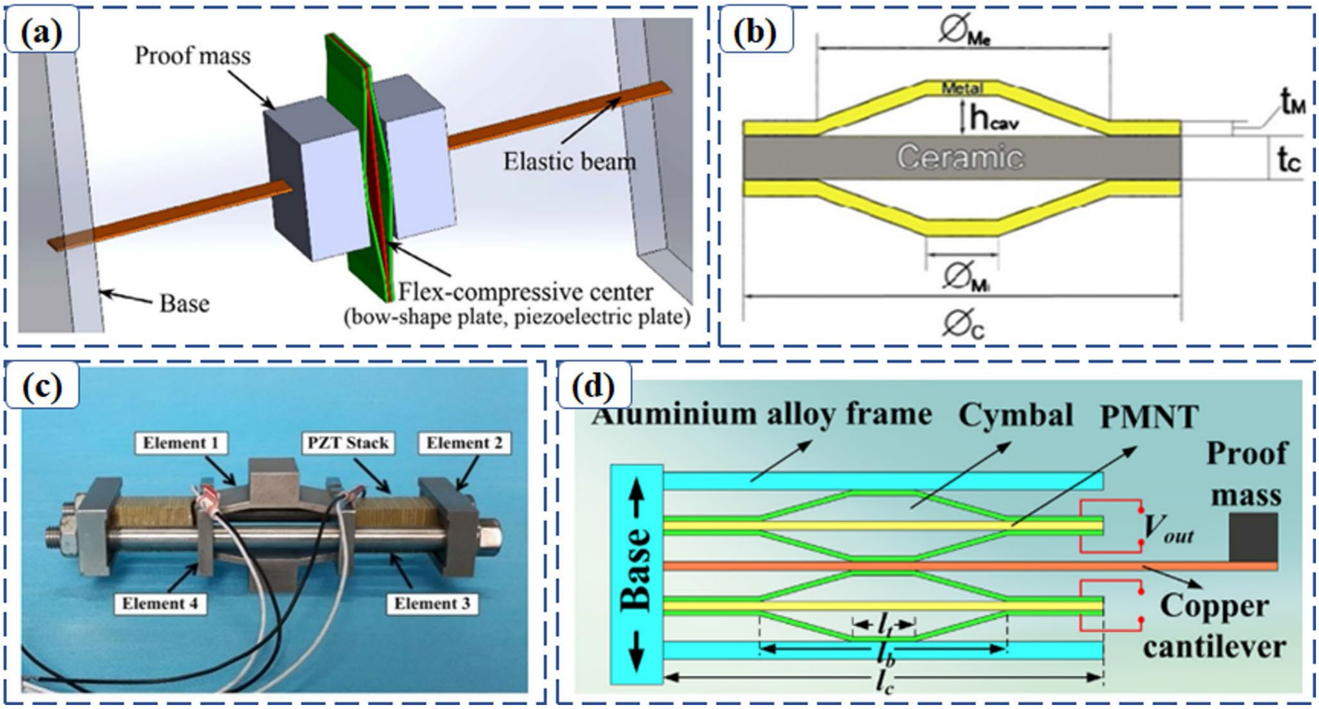

Fig. 5 Typical cymbal-type structures for PEH include (**a**) a high-efficiency compressive-mode energy harvester (Yang and Zu 2014), (**b**) Cymbal PZT with a diameter of 29 mm embedded (Moure et al. 2016), (**d**) a cantilever beam and cymbal harvester combined structure (Xu et al. 2012)

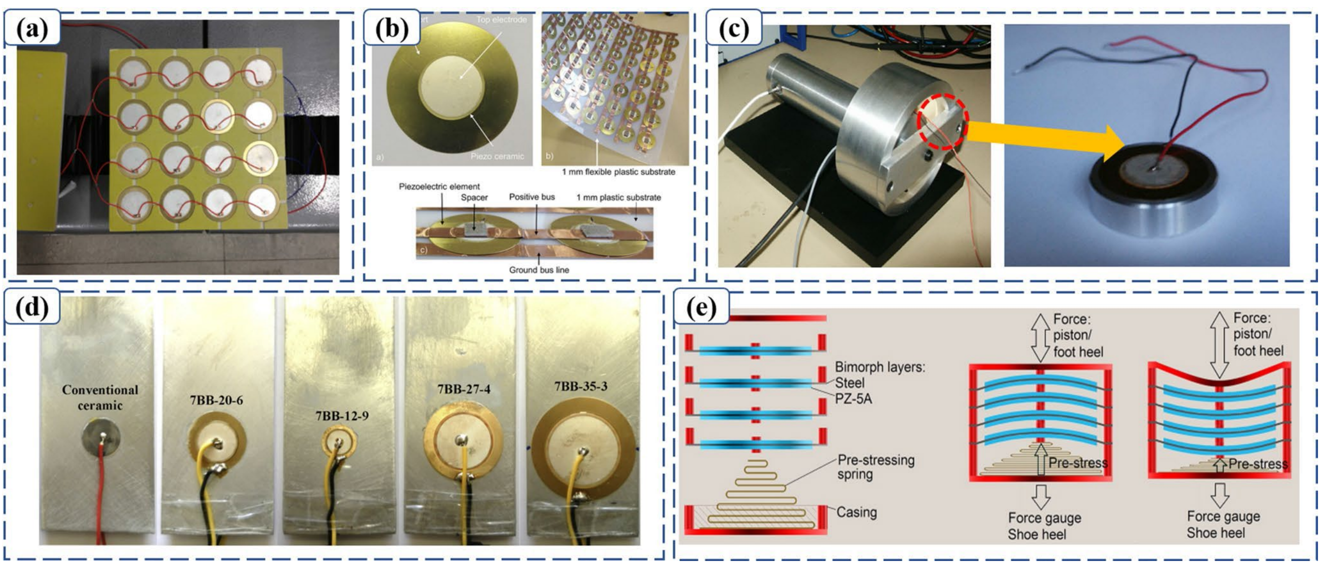

Fig. 6 Typical diaphragm structures for PEH include (**a**) and (**b**) an array of the piezoelectric diaphragm (Toprak and Tigli 2014; Naifar et al. 2017; Yang et al. 2018), (**c**) a stack of piezoelectric diaphragms (Leinonen et al. 2016), (**d**) and (**e**) a single piezoelectric diaphragm (Roundy et al. 2003; Lu et al. 2004; Gao et al. 2018)

2.4.1 Single crystal

Owing to their strong piezoelectric properties, piezoelectric single crystals such as lead magnesium niobate-lead titanate (PMN-PT), lead niobate-lead niobate (PNN), and lead magnesium niobate-lead titanate (PZN-PT) are commonly studied. Single crystals offer a higher piezoelectric constant and a lower elastic modulus compared to ceramics, making them more advantageous for small-scale piezoelectric energy harvesters (PEHs), as they can achieve resonance at lower frequencies (Kazys et al. 2017). However, single crystals have certain limitations that can constrain their applications. For example, their polarization properties may diminish under strong electric fields that are oriented opposite to the direction of polarization. Additionally, their manufacturing costs are generally higher than those of piezoelectric ceramics (Karami et al. 2011). While piezoelectric single crystals demonstrate higher power densities compared to ceramics, the output power of most single-crystal PEHs is typically in the microwatt range.

2.4.2 Ceramic

Piezoelectric ceramics can convert mechanical energy into electricity through a high-temperature sintering process that instills the piezoelectric effect (Yang and Zu 2016). Among these materials, the lead zirconate titanate (PZT) is commonly studied due to its stable piezoelectric properties and low dielectric constants. The primary configurations used in PEHs include PZT disks and stacks, as shown in Fig. 7. Depending on the specific characteristics required for energy harvesting, PZT can be employed in various structural forms. For instance, PZT stacked layers and cymbal structures are well-suited to withstand the stresses and impacts associated with capturing mechanical energy (Wang and Shi 2017a). In contrast, PZT cantilever beams, plates, and arrays are more advantageous for harvesting energy from acoustic sources, vibrations, and wind (Roundy and Wright 2004). The material characteristics of piezoelectric ceramics typically limit the resonance frequency of PEH prototypes to between 10 and 200 Hz, preventing excessively high frequencies. Notably, even a slight deviation—approximately 5%—from the ideal resonance frequency can cause a significant reduction in output voltage (Choi et al. 2013).

Although ceramic-based PEHs generally produce power at the milliwatt level and are well-suited for harvesting low-frequency vibration, their fragile nature and limited resistance to large strains pose constraints on their application. Furthermore, the presence of lead in PZT, despite its excellent piezoelectric properties, raises environmental concerns that may limit its broader application (Hu et al. 2019).

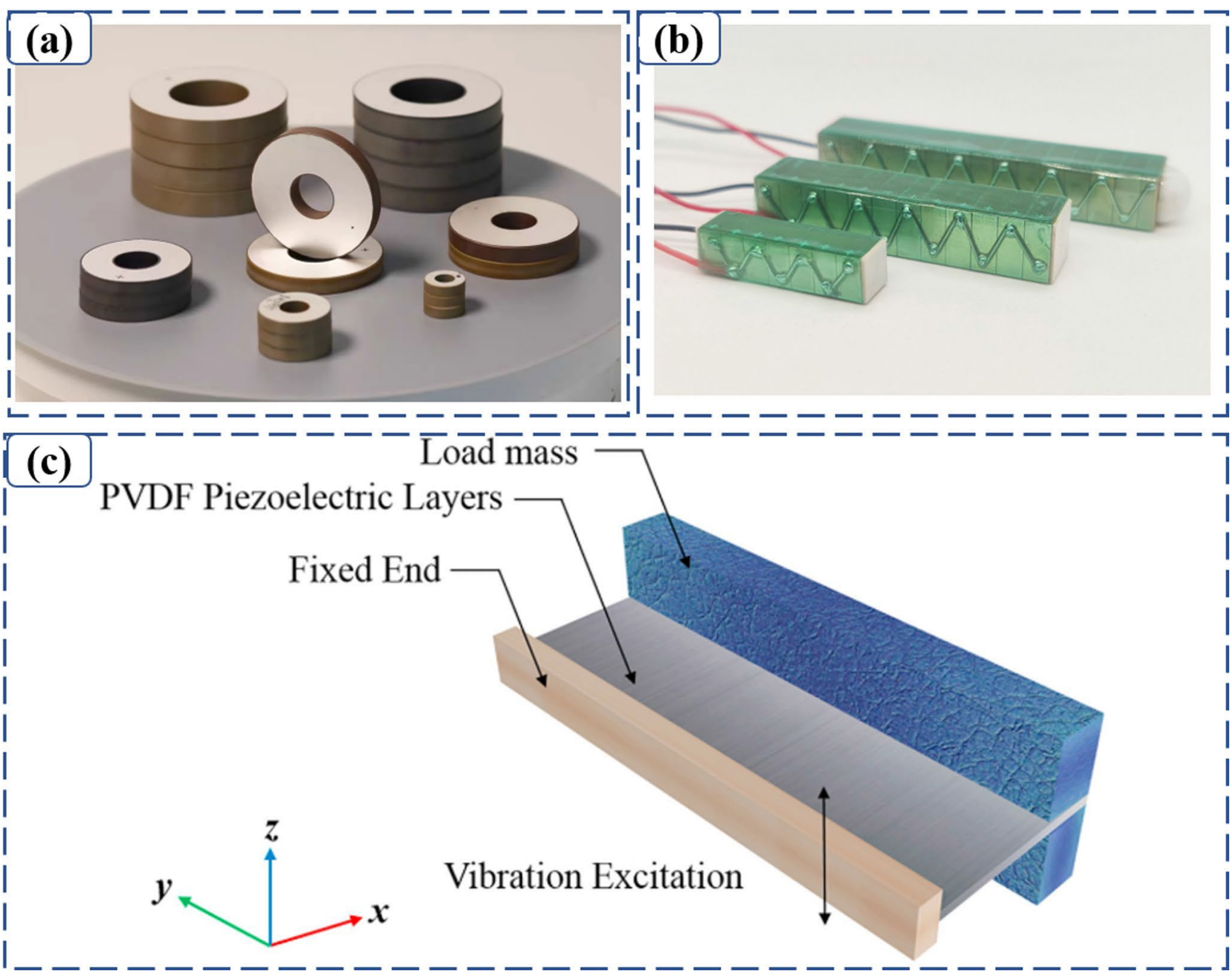

Fig. 7 Typical PZT and PVDF: (**a**) and (**b**) PZT stack (Habib et al. 2022), (**c**) PVDF harvester structure (Song et al. 2017)

Table 1 Properties for the typical piezoelectric single crystals, ceramics, polymers, and composites (Liu et al. 2018)

Notation	PZN-PT	PZT-5 A	PVDF	MFC
ρ	8.39	7.5	1.78	7.7
E	20.3	56	2	30.36
ε	5139	1800–1900	6	-0.9
d_{31}	-1075	-171	12–23	-171
d_{33}	2204	374	25	374
Q	40–100	80	10	75
k_{31}	>0.41	0.36	0.12	0.34
k_{33}	>0.89	0.72	0.15–0.22	0.71

2.4.3 Piezoelectric polymer

Piezoelectric polymers, such as polyvinylidene fluoride (PVDF), offer enhanced flexibility and are easier to bend compared to single crystals and ceramics. This flexibility enables the capture of vibration energy and facilitates installation on curved surfaces (Habib et al. 2022). PVDF stands out among piezoelectric polymers due to its high piezoelectric constant, as shown in Fig. 7(c). This polymer can be manufactured into diaphragms of various shapes and thicknesses to meet specific structural requirements. Additionally, with a density of only one-fourth that of lead zirconate titanate (PZT), PVDF is ideal for constructing lightweight PEHs (Hadas et al. 2020). PVDF-based PEHs are particularly effective in environments with very low frequencies (below 10 Hz) or high excitation amplitudes, as PVDF's inherent flexibility enhances its responsiveness to vibrations compared to ceramics. However, PVDF typically generates output power at the micro-watt level and exhibits a low electromechanical coupling coefficient (Li et al. 2014a).

2.4.4 Composite

While ceramics offer strong piezoelectric performance, their brittle nature limits their use in flexible PEHs. In contrast, polymers are highly flexible but lack sufficient piezoelectric properties for high-energy-density applications. To overcome these limitations, studies have proposed the development of piezoelectric composites that incorporate ceramic particles within a polymer matrix (Li et al. 2014a; Yang et al. 2020). Most of these composites combine the piezoelectric properties of ceramics, such as PZT, with the flexibility of polymers like PVDF. This approach harnesses the high piezoelectric performance of PZT and the flexibility of PVDF (Uchino 2017). These composites exhibit flexibility similar to PVDF, have a significantly lower stiffness coefficient compared to PZT, and their piezoelectric constant is only slightly lower than that of PZT. By doping PZT into polymers, composites can achieve output power comparable to PZT yet operate at slightly lower frequencies.

Table 1 reviews the parameters of typical piezoelectric materials, including single crystals, ceramics, polymers, and composites. These parameters encompass the dielectric constant (ε), indicative of charge storage capability; the piezoelectric constant (d), which quantifies the conversion of mechanical to electricity; the mechanical quality factor (Q), reflecting damping capacity; and the electromechanical coupling coefficient (k), a measure of the efficiency of energy conversion. The values of ε, d, and k are considerably higher in piezoelectric single crystals and ceramics compared to those in polymers and composites. In contrast, piezoelectric polymers, with a lower dielectric constant, are well-suited for applications in confined spaces and under high excitation amplitudes. Composites, blending the attributes of both polymers and ceramics, exhibit flexibility and improved piezoelectric properties.

As detailed in Table 2, the suitability of these materials for various applications depends on their strengths and limitations. Ceramics and single crystals share similar resonance frequencies, with single crystals operating in narrower frequency ranges (10–200 Hz) while ceramics require a broader application range due to their physical properties. These materials are commonly used for harvesting mechanical energy. Piezoelectric polymers are mainly effective in capturing vibration energy due to their softness. Piezoelectric composites, benefiting from their structural advantages, are well-suited for capturing mechanical, vibration, and wind energies.

Table 2 Summary of the advantages, drawbacks, and application of piezoelectric materials

Materials	Advantages	Drawbacks	Scenarios requirements
Single crystals	Large dielectric constant, small size	High-cost, easy to lose polarization	The small size of the PEH to capture vibration energy (10–200 Hz)
Ceramics	Great piezoelectric performance, low cost	Poor flexibility, brittle structure	Different structures of ceramics-based PEH to capture mechanical energy and vibration energy (10–200 Hz)
Polymers	Good flexibility, easy to resonate, lightweight	Poor piezoelectric performance	Harvesting the vibration energy (below 10 Hz) and wind energy, suitable for scenarios with high excitation amplitudes
Composites	Great piezoelectric performance, good flexibility	High cost, hard to produce	Suitable for flexible PEH to collect the mechanical energy and vibration energy

3 Piezoelectric energy harvesters for railways

Track irregularities, vibrations, and friction arising from wheel-rail interactions, as well as loads transmitted from rails to sleepers, noise, and wind generated during train operations, are common in railway environments. This section summarizes the application of PEHs in railways, focusing on their ability to capture energy from vibrations, mechanical movements, friction, sound and wind. It also compares the characteristics and potential applications of these energy harvesters across various railway scenarios.

3.1 PVEH

Piezoelectric vibration energy harvesters (PVEHs) have been increasingly studied to capture the vibration energy in railway environments, which originates from wheel-rail contact, train operations, and track infrastructure (Hou et al. 2021). These harvesters are typically installed on rails, sleepers, and bridges in an attempt to capture energy.

3.1.1 PVEH located on the rail

Rail, a fundamental component of track infrastructure, experiences vibrations generated at the wheel-rail contact due to track irregularities (e.g., differential settlement) and wheel irregularities (e.g., out-of-round wheels). Research has been conducted on the placement of PVEHs on various parts of the rail, such as the web and foot, to maximize the harvesting of vibration energy. Regarding the rail web, Gao et al. (Gao et al. 2016) developed a PZT cantilever harvester specifically designed to capture energy from rail vibrations, achieving an output power of 4.9 mW and a maximum voltage of 24.4 V at frequencies between 5 and 7 Hz, as shown in Fig. 8(a). Further advancing this technology, Li (Li et al. 2014c) explored the use of a cantilever array PVEH, which demonstrated increased power generation within the frequency range of 55–75 Hz, as depicted in Fig. 8(b). Another study by Nelson (Nelson et al. 2008) described a PZT cantilever harvester that produced an average power output of 1.1 mW under loaded train conditions, suggesting its potential to power low-power sensors, as shown in Fig. 8(c). Moreover, research by Yang (Yang et al. 2021; Dong et al. 2022), shown in Fig. 8(d), highlights the efficiency of cantilever PVEHs, which are three and fifteen times more effective than traditional harvesters at low and high dominant frequencies, respectively. Traditional harvesters are generally constrained to narrow frequency ranges and lack the adaptability and efficiency required for effectively capturing broadband vibrations. Shan et al. (Shan et al. 2022a, b) designed a piezoelectric harvester characterized by resonant frequencies of 17 and 20 Hz, intended to power wireless sensors, as shown in Fig. 8(e). To protect the PEH, Shan et al. (Shan et al. 2024) designed two protection methods for harvesters, involving ring-type and circular stoppers. These methods have demonstrated effective protection from unexpected railway vibration overloads, which makes a significant impact on the applications in the real-world. Unlike typical cantilevers, this harvester uses a cymbal structure to transform low-frequency vibrations into higher frequencies,

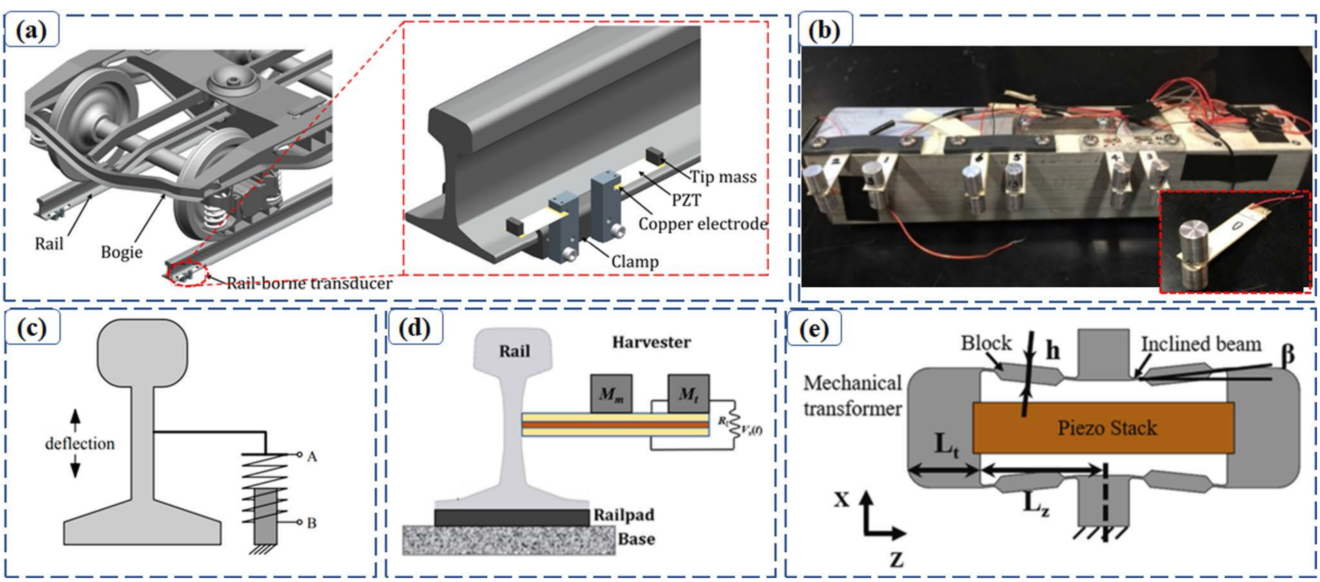

Fig. 8 PVEHs on the rail web include (**a**) a single DOF spring-resonant harvester (Gao et al. 2016), (**b**) a broad-band piezoelectric energy harvester (Li et al. 2014c), (**c**) a piezoelectric device to capture the energy of the longitudinal vibration (Nelson et al. 2008; Pourghodrat et al. 2014), (**d**) a piezoelectric cantilever with dual-mass configuration and trimly-tuned broadband (Dong et al. 2022), (**e**) an up-conversion piezoelectric stack energy harvester (Shan et al. 2022a)

successfully achieving a maximum power output of 6.72 mW.

A challenge associated with fixing energy harvesters to the rail web is the potential encroachment into the kinematic envelope. The kinematic envelope defines the zone within which no foreign objects can be placed without risking running contact between the wheel and rail. Strict limits for this envelope are defined in the national standards of the infrastructure owner and must be checked before deploying an energy harvester on the rail web.

Alternatively, the rail foot provides a viable location for extracting vibrational energy, as it is unlikely to encroach on the kinematic envelope. For example, Wang (Wang et al. 2013, 2015) investigated the effectiveness of a piezoelectric stack harvester for this purpose, as shown in Fig. 9(a). Theoretically, this harvester was capable of generating an average power output of 0.8 mW at train speeds of 324 km/h, which is five times greater than that of a traditional patch harvester. Similarly, Cao (Cao et al. 2022) designed a stack harvester, depicted in Fig. 9(b), which successfully captured 68.38 μJ of vibration as trains passed by. However, the electrical output from these stacks is generally limited due to their high stiffness, which hinders efficient vibration transmission. In a related study, Min et al. (Min et al. 2023) developed an innovative cymbal harvester, as shown in Fig. 9(c). This device achieved a maximum power output of 193 mW and an average output voltage of 260.14 V.

The findings from this study indicated that the cymbal structure has the potential for superior power generation efficiency compared to the stack design. However, generating significant power from rail-mounted energy harvesters remains challenging. The primary reason is that vibrations induced by wheel-rail irregularities exhibit low coherence between successive train passages and have a relatively broadband nature. Additionally, the quasi-static excitation due to wheel-load passage does not induce free vibration. As a result, there is no dominant natural frequency in this train-induced track excitation that an energy harvester could be specifically tuned to match.

3.1.2 PVEH located on the sleepers

Research has explored the use of PVEHs within railway infrastructure as a viable method for energy recovery and sensor power supply. Wischke et al. (Wischke et al. 2011) developed a four-cantilever harvester mounted on the surface of a sleeper, which not only harvests energy but also provides detailed information about the passing train, as illustrated in Fig. 10(a). Meanwhile, Hou et al. (Hou et al. 2021) designed an innovative piezoelectric harvester that combines cymbal and stack structures, embedding it within a floating concrete slab (FCS), as shown in Fig. 10(b). In a real-world application on a bridge, 144 PVEHs were deployed across 36 blocks of FCS, generating 31.4 kJ of energy—sufficient to sustain the routine operation of certain intermittent wireless sensors. Min et al. (Min et al. 2024a, c) proposed double-arch PEHs to improve energy capture efficiency and adaptability across different frequencies. In impact experiments, the device successfully lit 54 LEDs, demonstrating an energy density with potential practical application.

Furthermore, Li (Li et al. 2013) designed a piezoelectric harvester with a resonance frequency of 47.6 Hz, capable of generating 0.66 mW of power. However, this output was insufficient to power sensors, highlighting the limited conversion efficiency of single-cantilever PVEHs. This suggests a potential future direction for improving power generation capacity through the design of cantilever arrays.

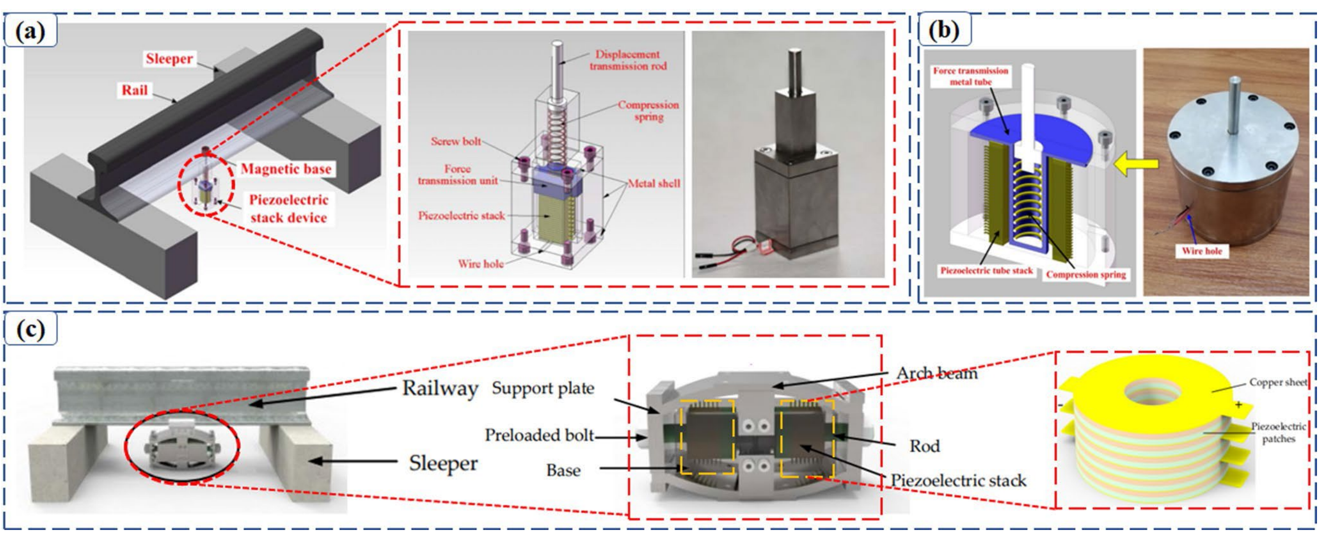

Fig. 9 PVEHs on the rail bottom include (**a**) a patch-type and stack piezoelectric harvester (Wang et al. 2015), (**b**) a piezoelectric tube stack energy harvester (Cao et al. 2022), (**c**) an arch beam piezoelectric stacking harvester (Min et al. 2023)

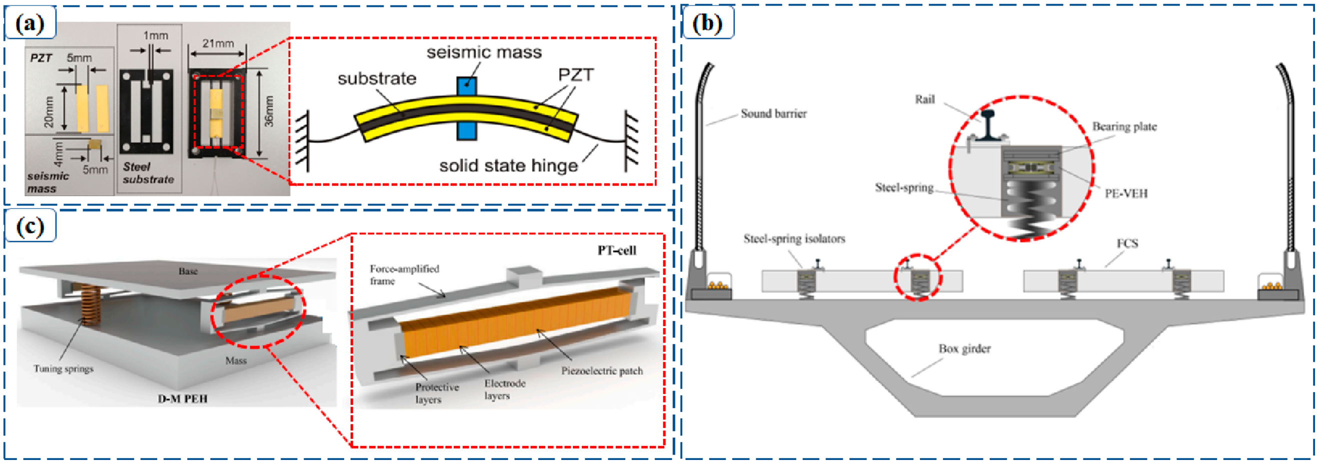

Fig. 10 PVEHs on the sleeper and bridge include (**a**) a four-cantilever piezoelectric harvester (Wischke et al. 2011), (**b**) a piezoelectric energy harvester combined cymbal and stack piezoelectric (Hou et al. 2021), (**c**) a dynamic-magnified piezoelectric harvester (Sheng et al. 2022)

3.1.3 PVEH located on bridges

For PVEHs located on bridges, Cahill et al. (Cahill et al. 2014, 2018) investigated the capture of vibration energy as trains passed over bridges using a cantilever PVEH tuned to the bridge's resonance frequency, generating 588 μW of power. However, this did not significantly enhance conversion efficiency. Li (Li et al. 2012a, b) developed a bimorph cantilever harvester that produced 0.74 mW of power at a natural frequency of 65.2 Hz. However, studies such as Romero et al. (Romero et al. 2021) demonstrated that whether tuned to the bridge's resonant frequency or the natural frequency of a single cantilever, power generation remained limited, with only 0.0151 mW collected at 0–10 Hz.

To improve efficiency, Romero (Cámara-Molina et al. 2024) proposed a new tuning strategy for bridge harvesters, which increased energy collection by 300% compared to traditional methods, but the total energy captured over three hours remained relatively low. To do so, a low-damping double-cantilever harvester was designed, gathering 109.32 mJ over three and a half hours and a total of 471.67 mJ when used in an array, potentially sufficient to power low-power devices and sensors for remote monitoring systems (Cámara-Molina et al. 2023). Alternatively, Zhang et al. (Zhang et al. 2018) deployed two PVEHs, PVEH-1 (aligned with the natural frequency of the bridge) and PVEH-2 (tuned to the frequency of vehicle-bridge coupling vibrations). Experimental results showed that PVEH-2 outperformed PVEH-1, generating voltage even when a train was on the bridge, whereas PVEH-1 failed to harvest energy. These findings suggest that PVEHs designed based on vehicle-bridge resonance frequencies perform better than those aligned with bridge-harvester resonance frequencies. However, implementing this approach could be challenging on lines with multiple rolling stock types. Given the generally low efficiency of PVEHs, Song (Song 2019) theoretically predicted a maximum voltage of 205.5 V for a newly designed cantilever PVEH. Further, Sheng (Sheng et al. 2022) developed an efficient piezoelectric stack harvester, depicted in Fig. 10(c), which achieved a maximum voltage of 603 V during train passage, substantially exceeding the outputs of traditional PVEHs.

3.2 PMEH

Mechanical energy is a prevalent form of energy in the railway environment and represents a promising source for energy harvesting (Sezer and Koç 2021). Research has highlighted the potential for the railway industry to exploit this energy using piezoelectric devices (Díez et al. 2019). The device specifically designed to capture mechanical energy is known as a piezoelectric mechanical energy harvester (PMEH) (Azam et al. 2021).

3.2.1 PMEH located on the rail

Alam et al. (Alam et al. 2012) proposed using a PZT patch trackpad to convert the mechanical stress exerted by train operations into electricity. Similarly, Datta (Datta and Mondal 2019) implemented a PZT patch trackpad. In 2009, Technion University of Israel installed 32 Innowattech piezoelectric trackpads, successfully harvesting 120 kW of electricity per hour (Sandru 2010). Min et al. (Min et al. 2024b) proposed doughnut-shaped PMEHs to collect the impact load energy, generating an output power of 207.67 mW. However, the high stiffness and brittleness of PZT, which primarily functions to resist vibrations, pose significant challenges. The intense vibrations and forces experienced in railway environments raise concerns about the longevity and durability of PZT trackpads.

The effectiveness of cantilever-based PVEHs, which rely on vibration frequencies to generate power, can be limited due to difficulties in matching the resonance frequency for stable energy output. In contrast, PMEHs do not depend on resonance frequencies, making them more suitable for capturing energy. Mishar (Mishra et al. 2021a, b) highlighted the superior efficiency and lower cost of compressive-PMEHs compared to cantilever-PVEHs, noting that the former generated 0.2 W of power, approximately ten times that of the latter. In laboratory settings, MFC and PVDF demonstrated promising performance, generating 1.5 V and 0.75 V respectively.

3.2.2 PMEH located on the sleepers

Railway sleepers secure the rails at the set track gauge and maintain alignment with the fastening system. "Piezoelectric sleepers" (Sone 2016; Jing et al. 2021; Wang et al. 2021), such as those developed by Green Rail (Green Rail 2022), incorporate a concrete core mixed with recycled plastic and rubber, as shown in Fig. 11(a). Wang et al. (Wang et al. 2022) embedded a smart backing ring containing 12 piezoelectric stacks into FCS, as shown in Fig. 11(b). This system achieved a maximum average power of 100 mW when a train passed at 100 km/h. accumulating 12.84 kJ of energy per day with 36 smart backing rings, sufficient to power a wireless temperature sensor. However, due to its high stiffness and brittleness, the piezoelectric stack is prone to failure under high cyclic stress. To mitigate this issue, a cymbal structure enhances energy harvesting while protecting the piezoelectric stack. Chen et al. (Chen and Li 2022) implemented a cymbal PMEH on a sleeper, generating an average power of 32.4 mW, as shown in Fig. 11(c). Similarly, to prevent damage, Wang and Shi (Wang and Shi 2017a, b) developed a cymbal stack harvester embedded within the sleeper, achieving a maximum output power of 0.62 W as a train passed at 144 km/h. Li et al. (Li et al. 2011) also explored a compressive-PMEH integrated into the sleeper. For scalability, Yuan et al. (Tianchen et al. 2014) proposed a piezoelectric patch array installed at sleeper bottom, as shown in Fig. 11(d). Numerical simulations indicated that this array could generate voltages ranging from 50 to 70 V in practical applications.

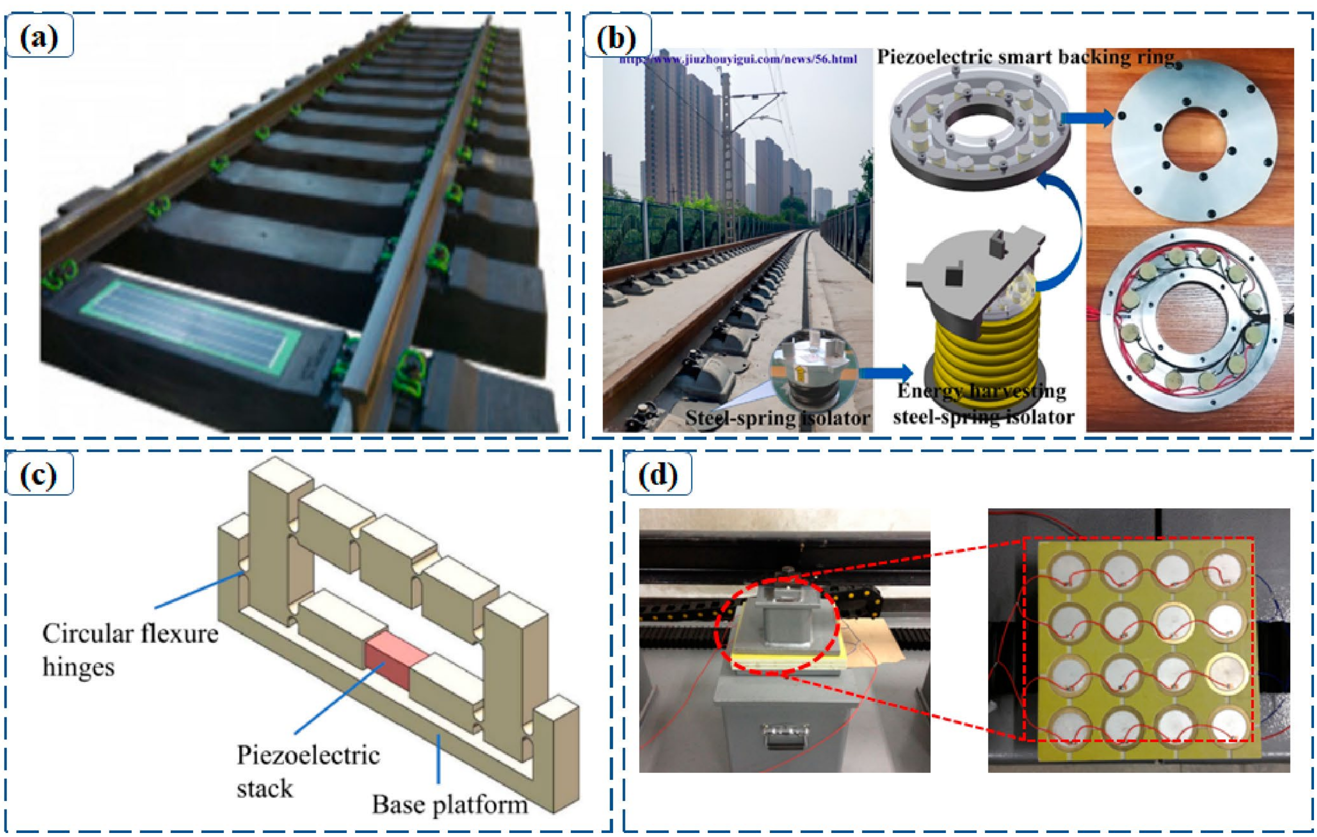

Fig. 11 PMEHs on the sleeper include (**a**) Green Rail Piezo (Green Rail 2022), (**b**) a piezoelectric smart backing ring with 12 piezoelectric stacks (Wang et al. 2022), (**c**) a PMEH based on the compliant mechanism (Chen and Li 2022), (**d**) a piezoelectric plate array at the bottom of sleeper (Tianchen et al. 2014)

3.3 PFEH

Friction braking systems in high-speed trains use friction at the braking interface to dissipate kinetic energy, ensuring the train halts within a safe distance (Ma et al. 2021; Peng et al. 2021). During braking, these systems generate vibration and noise due to friction (FIVN), which contributes to wear and deterioration of the braking components (Xiao et al. 2020; Stender et al. 2021). The FIVN produced by high-speed train braking systems represents a significant source of energy. This energy, characterized as self-excited vibration, is independent of external vibration sources. The piezoelectric energy harvester that collects this energy is called a piezoelectric friction energy harvester (PFEH).

3.3.1 PFEH general applications

Xiao (Xiao et al. 2023) introduced a harvester using the shear mode to capture the energy from FIVN. Experimental results confirmed the harvester's ability to capture high-frequency vibrations resulting from friction, although the efficiency of power generation in this mode was found to be suboptimal. Xiang (Xiang et al. 2021) explored a PZT cantilever harvester and analyzed the impact of its installation orientation. The study revealed that the harvester oriented in a normal-tangential direction exhibited the highest power generation capacity, producing a voltage of 2 V, as shown in Fig. 12(a). Chen (Chen et al. 2020) developed a sandwich PFEH, featuring two elastic pads and piezoelectric patches, as shown in Fig. 12(b). This design reduced vibration and harvested energy during braking events. Building upon this, Xiang et al. (Xiang et al. 2022) investigated a sandwich PFEH with holes, shown in Fig. 12(c), and demonstrated that its output voltage was approximately 140% higher than that of a conventional sandwich PFEH. These studies suggest that cantilever PFEHs are particularly advantageous for harvesting friction-induced high-frequency vibrations, providing significant capacity for power generation (Lu et al. 2023).

3.3.2 PFEH based on stick-slip motion

Studies suggest that stick-slip motion is a likely mechanism for generating friction-induced energy (Ghazaly et al. 2013). Tadokoro et al. (Tadokoro et al. 2017) investigated this phenomenon between steel balls and steel plates, confirming the potential for harvesting FIVN energy through stick-slip motion. Masuda (Masuda and Sawai 2017) employed an L-shaped cantilever harvester to capture energy from stick-slip motion, as depicted in Fig. 13(a). Helseth (Helseth

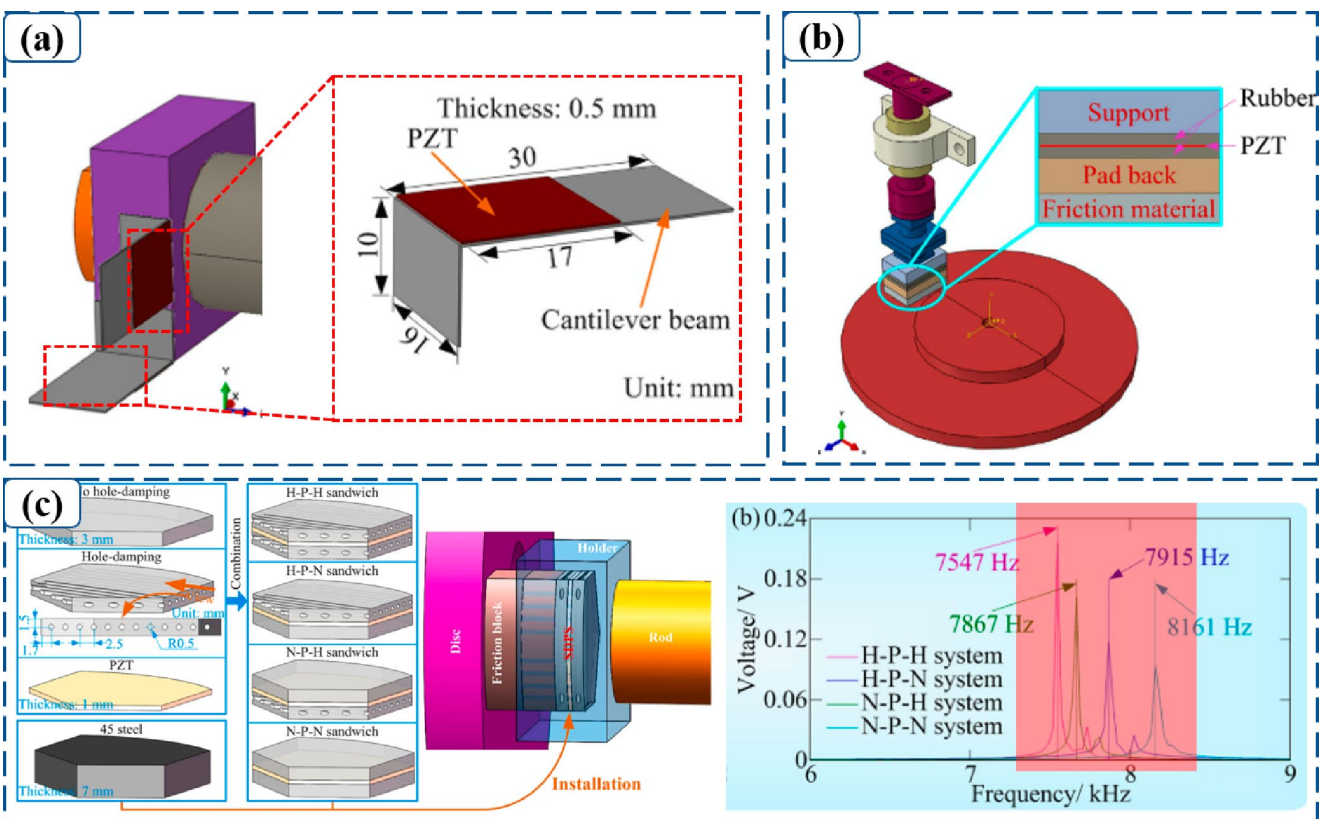

Fig. 12 General PFEHs include (**a**) a normal-tangential piezoelectric harvester (Xiang et al. 2021), (**b**) a sandwich PFEH (Chen et al. 2020), and (**c**) a sandwich PFEH with holes (Xiang et al. 2022)

2014) developed a harvester that exploits stick-slip motion between hooks and loops, achieving maximum power output under specific normal loads and sliding velocities. Chen et al. (Chen et al. 2023) examined the effectiveness of vibration reduction and energy harvesting in a PFEH using a linear PZT design targeted at stick-slip vibrations, as shown in Fig. 13(b). Sani (Sani et al. 2024) addressed energy generation at low relative speeds by using a high-order Neimark-Sacker bifurcation, demonstrating the potential of unbalanced vehicle vibrations to improve the performance of energy harvesting in PFEHs.

Linear cantilever piezoelectric harvesters are commonly used to capture FIVN energy. These harvesters experience external excitations that cause the piezoelectric elements to bend, generating electricity. However, the power generation capacity of these linear harvesters is constrained by their narrow resonant bandwidth. When the frequency of friction-induced vibrations does not align with the harvester's resonance frequency, conversion efficiency drops significantly. Although tuning mechanisms and up-conversion mechanisms can enhance performance, they increase spatial requirements and reduce power density. In contrast, a nonlinear bistable cantilever harvester, proposed by Chen (Chen et al. 2024) and shown in Fig. 13(c), extends the frequency range and increases power output. This harvester has been both theoretically and experimentally shown to generate electrical power when triggered by large-amplitude periodic motions induced by stick-slip motion.

3.3.3 PFEH based on coupling vibration

The coupling between different vibration modes within friction-induced vibrations is recognized as an important mechanism (Ghazaly et al. 2013). Typically, stick-slip motion represents a single-degree-of-freedom (DOF) friction system, while mode coupling involves a multi-DOF friction system. Wang et al. (Wang et al. 2020a) evaluated the conversion efficiency of a piezoelectric harvester under both stick-slip and mode coupling mechanisms. The results showed that the single-DOF harvester exhibited pronounced stick-slip motion with an excitation load of 30 N, leading to higher electricity generation. In contrast, the double-DOF harvester produced a higher output voltage when subjected to an excitation load of 120 N. Based on these findings,

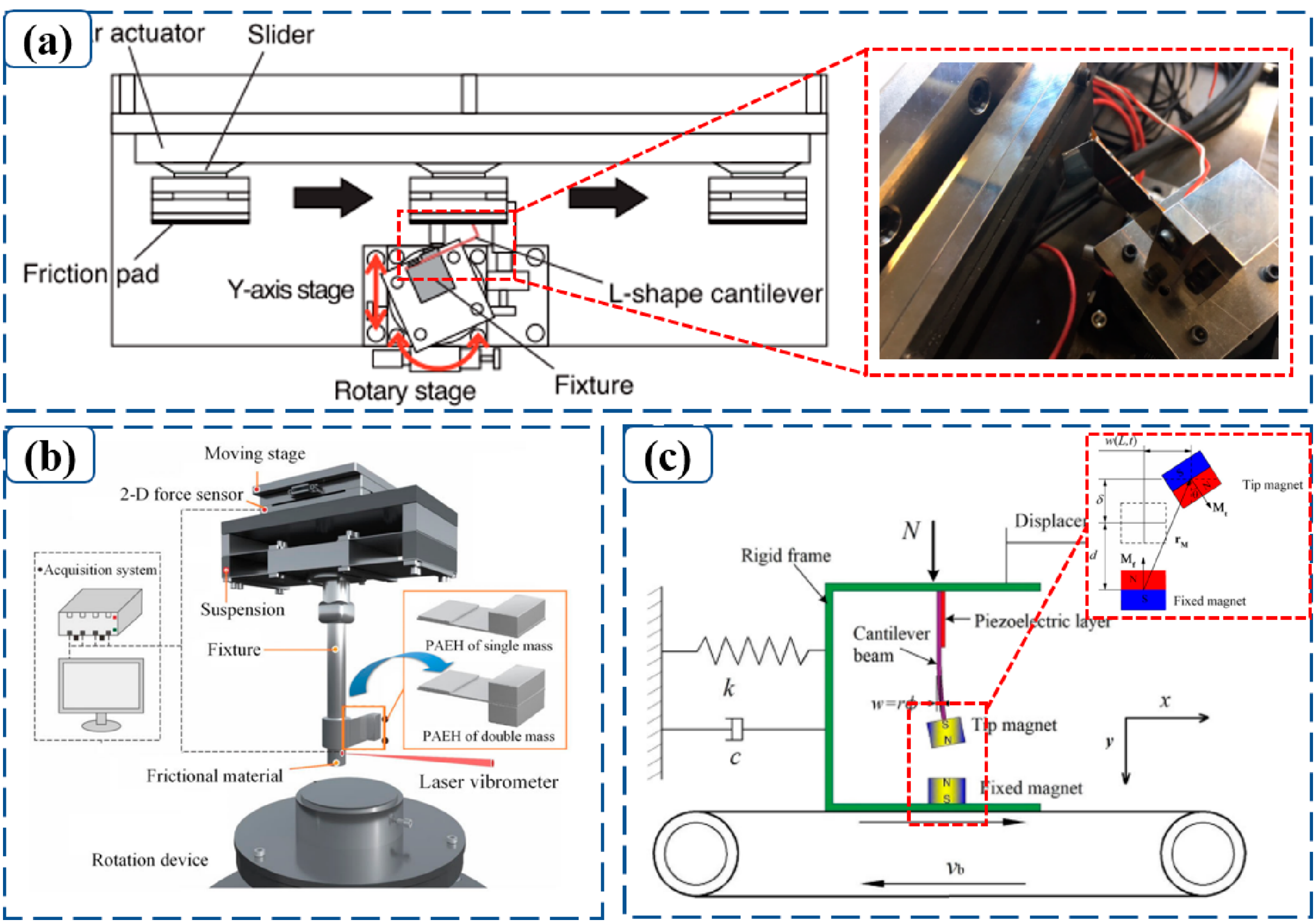

Fig. 13 PFEHs based on stick-slip motion include (**a**) an L-shaped cantilever piezoelectric harvester (Masuda and Sawai 2017), (**b**) a PFEH based on linear PZT (Chen et al. 2023), (**c**) a nonlinear bistable cantilever harvester (Chen et al. 2024)

Xiang (Xiang et al. 2023) proposed a five-DOF cantilever harvester, which consistently provided stable and continuous output voltage sufficient to power low-power sensors.

3.4 PSEH and PWEH

Noise and wind energy, both natural and generated by trains, are prevalent along railway lines (Esu et al. 2016; Hosseinkhani et al. 2021). Typically, noise and wind energy are captured using cantilever harvesters, which are called piezoelectric sound energy harvester (PSEH) and piezoelectric wind energy harvesters (PWEH) respectively, with research often focusing on the natural frequency of these harvesters to assess their power generation performance.

3.4.1 PSEH applications

Gieva (Gieva et al. 2019) explored the potential of PEHs, specifically for noise, referred to as PSEHs. A key component in PSEH systems is the Helmholtz resonator (HR), which amplifies sound pressure (Liu et al. 2023). Yuan (Yuan et al. 2021) introduced a novel design combining a PZT circular patch with a HR, achieving a resonant frequency of approximately 831 Hz in the PSEH system. Simulation results suggested this system generated an output power of 25 μW and a maximum voltage of 0.149 V under sound excitation, as shown in Fig. 14(a). Additionally, Hassan (Hassan et al. 2023) developed a PZT barrier for low frequencies below 200 Hz, generating voltages of 15 V and 18.2 V under sound pressures of 85 dB and 100 dB respectively, as shown in Fig. 14(b). Li et al. (Li et al. 2022a) designed a tunable PSEH for railway tunnels, as shown in Fig. 14(c). This device, operating within a frequency range of 200–1000 Hz and a pressure of 100 dB, generated a maximum voltage of 0.317 V, which is 11.5 times higher than PSEHs without resonance frequency tuning. Moreover, a dual-band PSEH was developed (Li et al. 2021a), incorporating an HR to amplify resonance, as shown in Fig. 14(d). This device achieved maximum voltage and power outputs of 3.2 V and 0.13 mW respectively, yielding an output power 12.7 times greater than conventional PSEHs.

In addition to PZT, other materials such as PVDF and MFC are also used in PSEHs. For instance, Wang et al. (Wang et al. 2018) designed a PSEH using HR and PVDF film, generating a voltage of 0.052 V. When integrated into a sound barrier with multiple PSEH arrays, the total voltage reached 35.8 V at a sound pressure of 110 dB, as shown in Fig. 15.

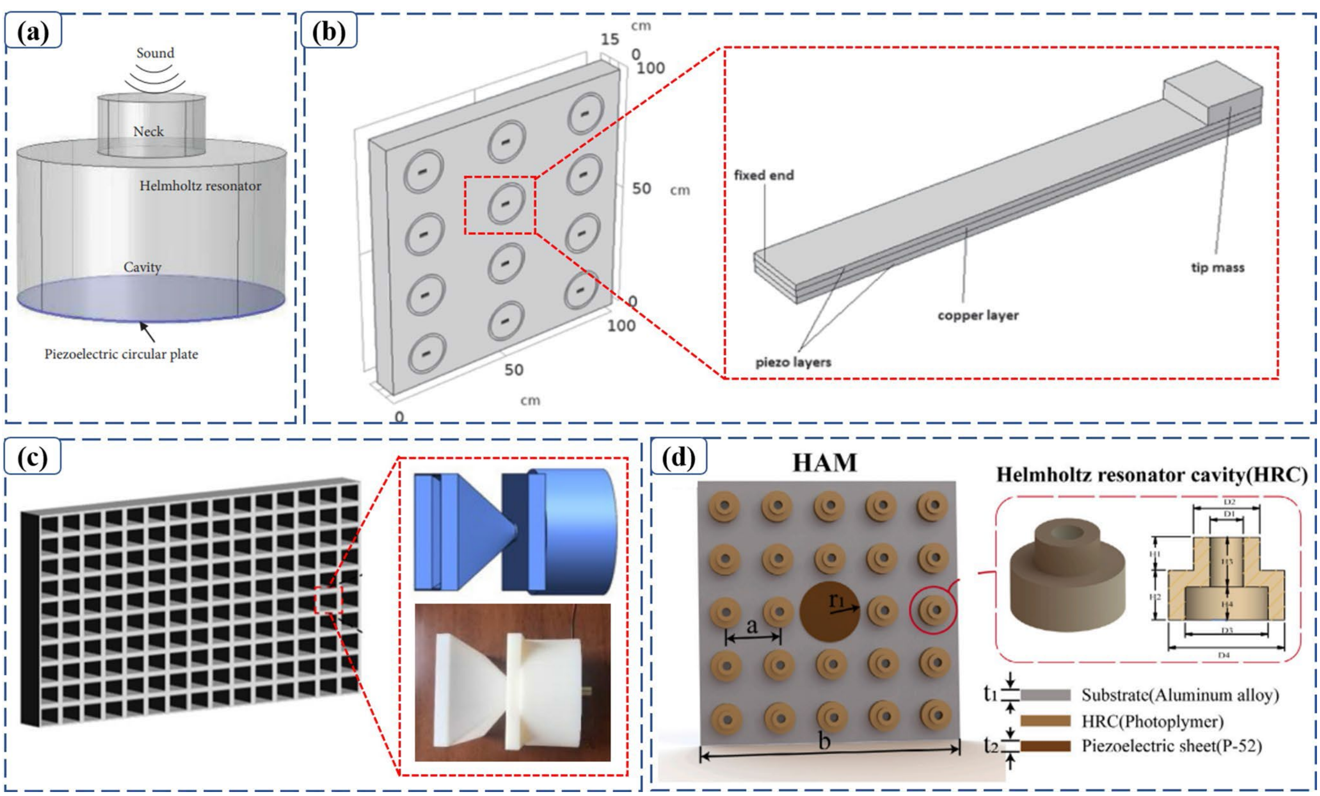

Fig. 14 PSEHs based on PZT include (**a**) an innovative acoustic energy harvesting system (Yuan et al. 2021), (**b**) an array of piezoelectric cantilever plates (Hassan et al. 2023), (**c**) a tunable and low-frequency sound energy capturing barrier (Li et al. 2022a), (**d**) a dual-band acoustic energy harvesting piezoelectric acoustic energy wall (Li et al. 2021a)

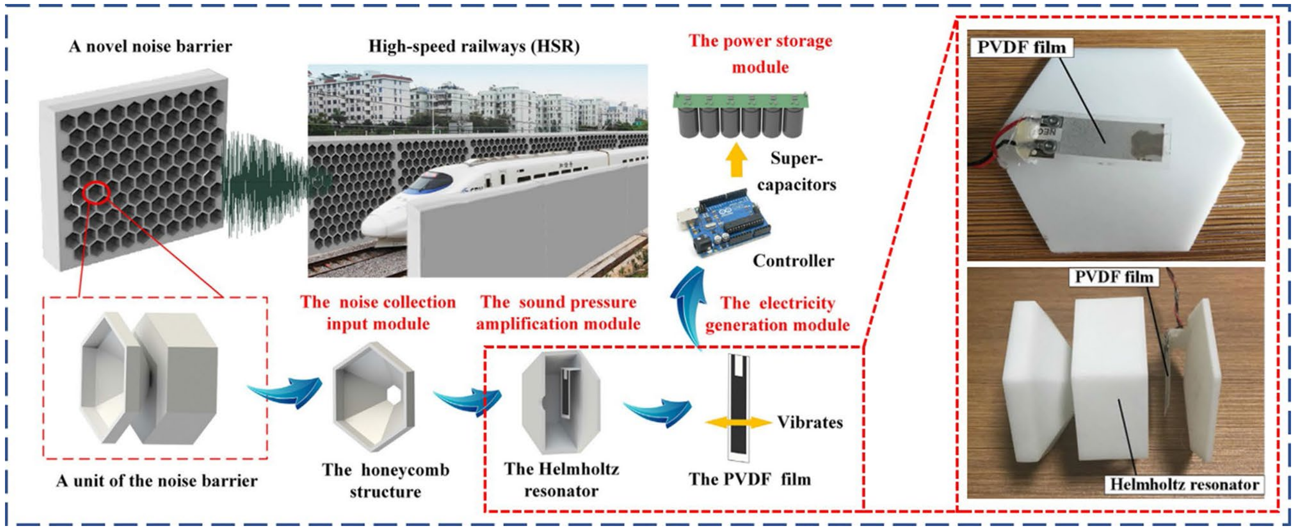

Fig. 15 A renewable PSEH based on PVDF (Wang et al. 2018)

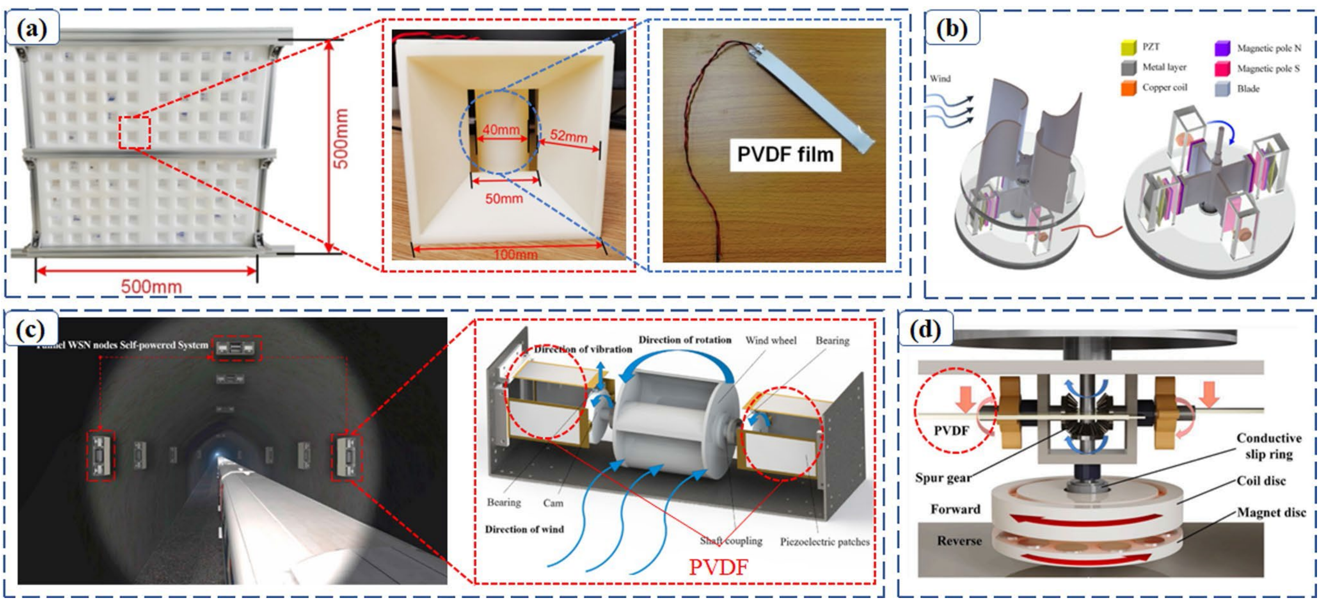

Fig. 16 PWEHs include (**a**) a wind energy barrier based on PVDF (Wu et al. 2022), (**b**) a wind energy harvester with piezoelectric and electromagnetic modules (Zhao et al. 2019), (**c**) a self-powered system with piezoelectric and electromagnetic module (Zheng et al. 2021), (**d**) a wind energy harvester based on PVDF (Zhou et al. 2023)

3.4.2 PWEH applications

3.4.2.1 Natural wind energy Wu et al. (Wu et al. 2022) developed a renewable barrier using PVDF along the Qinghai-Tibet Railway to harvest natural wind energy, as shown in Fig. 16(a). Wind tunnel tests demonstrated that single barrier cells can generate a maximum voltage of 13.61 V at a wind speed of 17 m/s, capable of charging a 47 μF capacitor to 2.21 V within 50 s. Similarly, Xue et al. (Xue et al. 2025) designed a wind barrier to optimize wind energy harvesting while maintaining its windproof function. Experimental results showed that wind barriers can generate a maximum power of 0.233 mW. Wind turbine harvesters are another typical device for converting natural wind energy into vibrations, which produce electricity through the piezoelectric effect (Zheng et al. 2023). These harvesters often integrate both piezoelectric and electromagnetic effects to broaden the range of acceptable wind speeds (Li et al. 2022b). For example, Zhao (Zhao et al. 2019) proposed a PWEH that integrated piezoelectric and electromagnetic modules, as shown in Fig. 16(b), which exhibited flexibility and conversion efficiency in practical applications. Similarly, Zheng (Zheng et al. 2021) designed a self-powered system consisting of electromagnetic, piezoelectric modules, as depicted in Fig. 16(c). This system converted wind energy into electricity via the electromagnetic effect while the piezoelectric patch also contributed to energy generation. To improve the efficiency of PWEHs, Zhou et al. (Zhou et al. 2023) introduced an enhancement method involving a dual-rotor reverse cooperative mechanism, as shown in Fig. 16(d). This mechanism enabled reverse rotation, improving the system's efficiency by 34% compared to a single rotor harvester, with the output power reaching 394 mW.

3.4.2.2 Train-induced wind energy Wang (Wang et al. 2017) introduced a flexible PWEH to collect wind energy induced by trains. This harvester produced an average voltage of 48.8 V and a maximum power of 5 W in its horizontal configuration, outperforming the vertical PWEH by approximately 20 times. Cantilever PWEHs, which are more responsive to external excitations, tend to generate electricity more effectively than stacked PWEHs (Wang et al. 2020c). However, it is important to note that harvesting wind energy solely through piezoelectric effects has its limitations. While piezoelectric harvesters capture more energy at low wind speeds, their conversion efficiency at high wind speeds can be suboptimal. A novel piezoelectric-electromagnetic harvester by Iqbal et al. (Muhammad Iqbal and Khan 2018) produced voltages of 114 mV and 25 mV from its piezoelectric and electromagnetic components, respectively, at a wind speed of 6 m/s. Xu et al. (Xu et al. 2025) introduced a dual-mode PWEH designed to effectively capture both train-induced wind energy and vibrational energy. Experimental results showed that the device activated the chip at 116.2 s, providing a potential solution for low-power consumption sensors.

3.5 Comparison and discussions

The design of medium and low-power PEHs primarily focuses on vibration-based and load-based devices, particularly suitable for the railway sector. PEHs based on friction, noise and wind energy can be considered a subtype of PVEHs due to their similar energy characteristics. For PFEHs, innovations in multi-DOF systems and multi-stable nonlinear designs can extend the operating frequency range and enhance efficiency. Helmholtz resonators are used to amplify sound pressure, thereby increasing the power output of PSEHs. PWEHs improve energy extraction efficiency by incorporating wind rotors, which expand the acceptable wind speed range, making them suitable for dynamic environments like railway systems.

Table 3 lists and compares the advantages and limitations of PEHs in harvesting different types of energy. While common structures such as PVEHs can generate milliwatts of power, this is often insufficient for practical applications. Key research areas should focus on optimizing the structure, resonant frequency, and nonlinear behavior to improve efficiency. Innovations such as arrays, cymbal structures, and resonance frequency optimization have enhanced output power, making these harvesters more suitable for powering low-power sensors. In addition, PEHs based on friction, noise and wind energy can be considered a subtype of PVEHs due to their similar energy characteristics. For PFEHs, innovations in multi-DOF systems and multi-stable nonlinear designs can extend the operating frequency range and enhance efficiency. Helmholtz resonators are used to amplify sound pressure, thereby increasing the power output

Table 3 Comparisons of PEHs based on different energy sources for the railway

Energy sources	Advantages	Drawbacks	Applications
Vibration energy (PVEHs)	-High power density -High output voltage -Simple design	-Low output power -Poor reliability -Performance degradation when not resonant	-Cantilever array enhances energy harvesting -Resonant frequency and broadband improve conversion efficiency
Mechanical energy (PMEHs)	-High output power -Simple design -Low cost	-Vulnerable to damage -Difficulty in installation -Poor compatibility with concrete	-Flexible and cymbal structure enhance conversion efficiency -Embedded structure improves durability of PEH
Friction-induced energy (PFEHs)	-High output power -High efficiency	-Complex design -Difficulty in installation -High cost	-Nonlinear and sandwich structures broaden frequency and improve power -Multi-stable state and DOF enhance efficiency
Sound energy (PSEHs)	-Mature technology -Easy to install	-Combined with HR -Work only when trains pass by	-Helmholtz resonator amplifies sound pressure to increase power output
Wind energy (PWEHs)	-Mature technology -Easy to install	-Low output power -Poor reliability -Work only when trains pass by	-Multiple mechanisms improve energy extraction efficiency

of PSEHs. PWEHs improve energy extraction efficiency by incorporating wind rotors, which expand the acceptable wind speed range, making them suitable for dynamic environments like railway systems.

PMEHs can convert stress into electricity but face challenges due to their high stiffness, strong coupling, and vulnerability to damage under cyclic stress. While some researchers have embedded PMEHs in concrete to mitigate damage, compatibility issues and altered stress distribution can reduce the service life of concrete infrastructure. Therefore, the most critical factor in optimizing the long-term performance of PMEHs is maintaining stiffness consistency, which is essential to enhance their durability and lifespan.

4 Key technologies and future directions

Research on PEHs for capturing ambient energy is ongoing, yet practical applications still face challenges, such as low conversion efficiency, limited output power, and safety concerns. Typically, PEHs are integrated into railway intelligent monitoring systems to power supply devices, as shown in Fig. 17. However, practical applications must account for factors like sensor selection, circuit integration, data transmission, and communication equipment. Thus this section will address the technical challenges encountered in the implementation of PEHs within the railway sector. Additionally, based on recent advancements in this field, recommendations for future research will be provided.

4.1 Powering wireless sensors

Emerging trends in railway development point towards smart railways, artificial intelligence, and the Internet of Things (IoTs). An important component of this modernization is the self-powered system, essential for smart railway operations (Jo et al. 2017). Some proposed smart railway systems envisage the placement of sensors and small-scale electronic devices on both the track and rolling stock for real-time monitoring and information interaction. If powered by batteries, these devices require regular manual replacements, incurring substantial maintenance costs. Therefore, if PEHs can meet the power needs of these low-power sensors, they offer an attractive solution for intelligent monitoring. For example, a wireless temperature sensor for monitoring axle boxes and bearings powered using a double-cantilever harvester has the potential to extend the sensor's lifespan by 20% compared to traditional battery-only systems (Dziadak et al. 2022). Similarly, series PVEHs have been demonstrated to power sensor monitoring temperature and humidity in vehicles (Mouapi et al. 2016; Wang et al. 2019), as shown in Fig. 18(a). The array of PVEHs designed by Sheng et al. (Sheng et al. 2025) generates 0.4 W of power, which can supply power to WSNs. Moreover, accelerometers and RF sensors can also be powered by PVEHs (De Pasquale et al. 2012), as shown in Fig. 18(b). Nonlinear PEHs are used to power sensors monitoring train vibration and acceleration, with low-power Bluetooth sensors (Cho et al. 2016; Shan et al. 2023). By integrating piezoelectric and

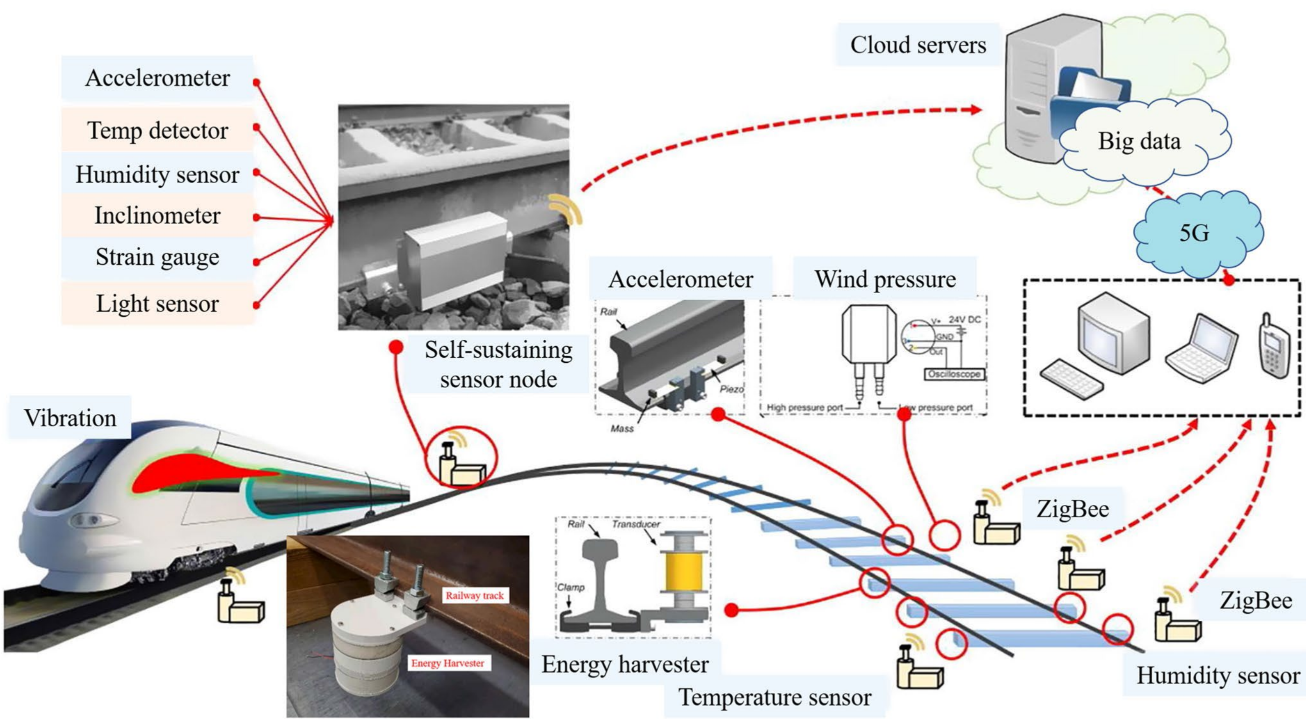

Fig. 17 Smart railway monitoring system (Gao et al. 2017)

electromagnetic effects, certain harvesters can power Bluetooth sensors and enable data transmission to smartphones, as shown in Fig. 18(c). Additionally, hybrid harvesters combining piezoelectric and solar effect exhibit energy conversion efficiencies ranging from 75 to 85% (Li et al. 2014b; Jung et al. 2020), as shown in Fig. 18(d) and (e).

A practical implementation of these devices is shown in the Powerrail device by Viezo, as shown in Fig. 19(a), which monitors wheelsets and bogies using a PVDF-based harvester called PolyFilm (Viezo 2021, 2024). This system, along with Hitachi Rail's integration of IoT-based smart management systems using Perpetuum's wireless sensor, not only extends the lifespan of critical components like wheel bearings but can also improve maintenance efficiency (Hitachi Rail 2020). In the UK, the rolling stock in multiple regions has adopted such monitoring systems, thus demonstrating their potential for operational use, particularly in enhancing maintenance procedures (Network Rail 2023). In addition, a wireless sensor powered by PEHs developed by the University of Exeter and Network Rail can be used to monitor the environment and track conditions (Network Rail 2022), as shown in Fig. 19(b). Also, a sensor developed by Encorete (Encorete 2023) monitors track temperature and vibration, as shown in Fig. 19(c). Furthermore, the PEHs designed by Feonic (Feonic 2024) can power the sensor and facilitate the wireless transmission of real-time data to the Cloud, as shown in Fig. 19(d).

Current advancements of PEHs focus on developing nanoscale, miniaturized self-monitoring systems, as summarized in Table 4. The trend towards low-power wireless sensors indicates a potential future of smart monitoring systems and IoTs, where PEHs are useful.

4.2 Interface circuits research

In recent years, the focus of PEHs within the railway industry has predominantly been on energy harvesting, often overlooking the aspects related to energy conversion and usage. The design of the interface circuit plays a crucial role in the application of PEHs. This circuit is responsible for storing the electric energy captured by the PEH or powering equipment, ensuring that the energy is effectively captured and utilized. Most sensors and electronic devices used in railways, suitable for powering through energy harvesting, require a stable DC power supply, yet piezoelectric harvesters generate AC. This necessitates the use of rectifiers for AC-DC conversion. After rectification, the resulting voltage often does not align with load requirements, requiring further DC-DC conversion. These circuit complexities present significant challenges to the broader application of piezoelectric harvesters in smart railways and self-powered monitoring systems.

The full-bridge rectifier (FBR) is commonly used for AC-DC conversion, but it suffers from low conversion efficiency due to diode forward voltage drops and impedance

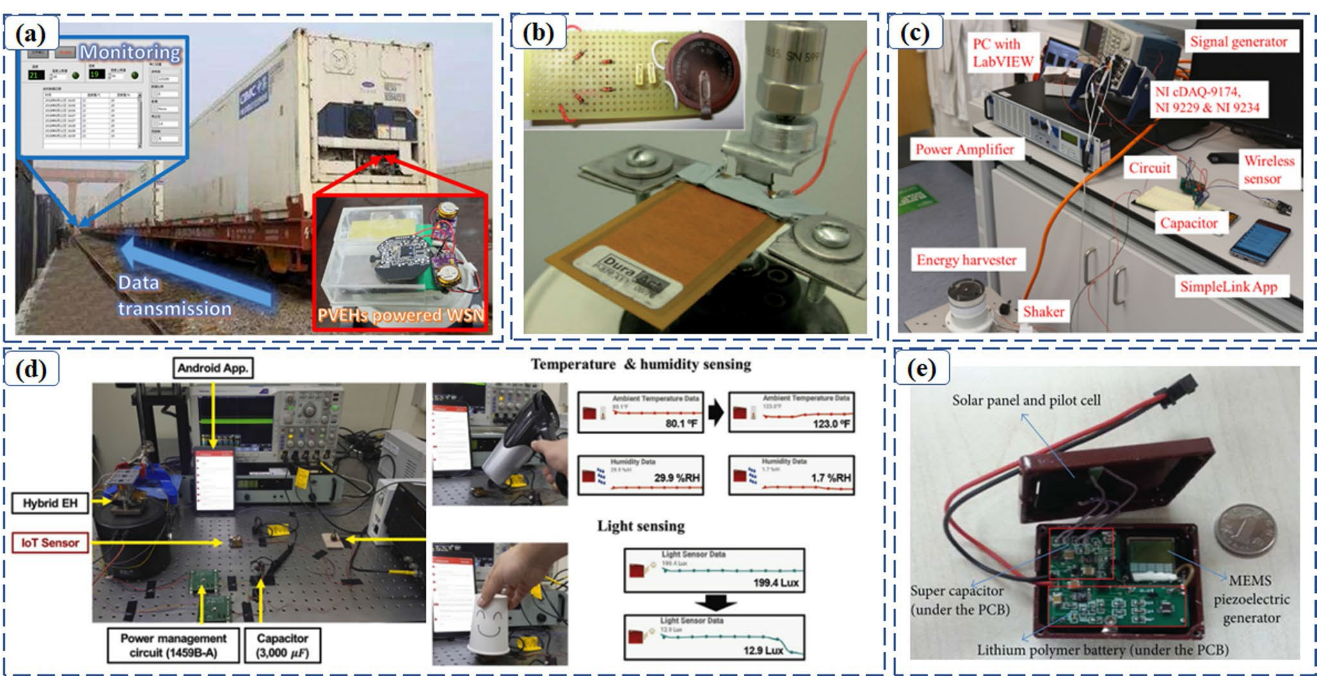

Fig. 18 Self-power monitoring systems powered by PEHs include (**a**) powering the temperature and humidity sensors (Wang et al. 2019), (**b**) powering the accelerometer and RF sensor (De Pasquale et al. 2012), (**c**) powering the Bluetooth sensor (Shan et al. 2023), (**d**) powering the Bluetooth sensor (Jung et al. 2020), (**e**) powering the autonomous and efficient operation of sensor (Li et al. 2014b)

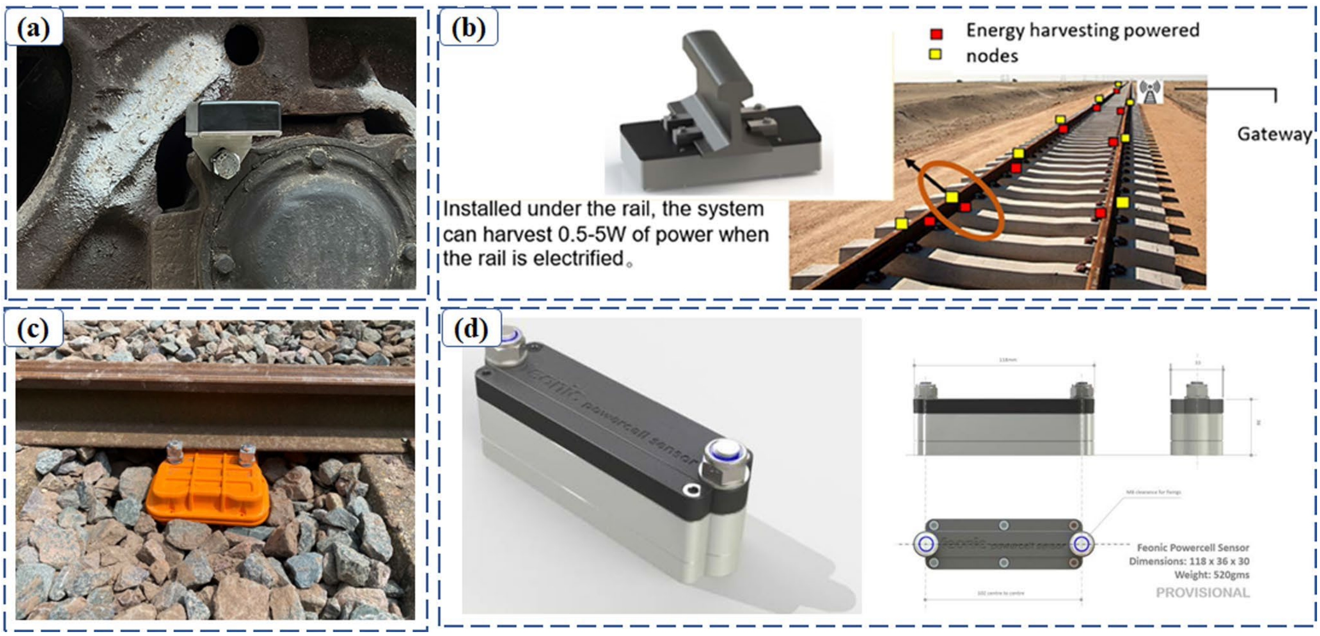

Fig. 19 Self-power monitoring applications powered by PEHs including (**a**) Power rail device (Viezo 2024), (**b**) Energy harvesting powered wireless sensor systems (Network Rail 2022), (**c**) Self-powered wireless sensors (Encorete 2023), (**d**) Feonic smart sensor (Feonic 2024)

Table 4 Comparisons of self-power monitoring systems powered by PEH

	Year	Energy sources	Sensor type	Power	Frequency
(Dziadak et al. 2022)	2022	Axle box vibration	Temperature sensor	60.5 µW	4–10 Hz
(Wang et al. 2019)	2019	Freight vibration	Temperature and humidity sensor	0.1 mW	8.7–22 Hz
(Mouapi et al. 2016)	2016	Train vibration	Temperature and humidity sensor	4.7 mW	26 Hz
(De Pasquale et al. 2012)	2011	Axle box vibration	accelerometers and RF sensor	-	6.8–10.6 Hz
(Wischke et al. 2011)	2011	Sleeper vibration	RF sensor	-	437–498 Hz
(Cho et al. 2016)	2016	Train vibration	Vibration sensor	40.24 $\mu W/cm^3$	3–6 Hz
(Shan et al. 2023)	2023	Track vibration and mechanical energy	Bluetooth sensor	7.3 mW	152 Hz
(Jung et al. 2020)	2020	Vibration	Bluetooth sensor	25.45 mW	60 Hz
(Li et al. 2014b)	2014	Vibration and solar	WTHS-G0 sensor	2–6 mW	44 Hz
(Yang et al. 2017a)	2017	Vibration, magnetic and thermoelectric	ZigBee sensor	0.63 mW	Near 100 Hz
(Viezo 2024)	2022	Vibration	Vibration and temperature sensor	-	-
(Hitachi Rail 2020)	2021	Vibration	Perpetuum sensor	-	-
(Sheng et al. 2025)	2025	Vibration	Displacement and strain sensor	4 W	-

mismatches (Wang et al. 2016). To enhance conversion efficiency, the switch-based rectifier circuit (SSHI) has been developed, which increases energy extraction by 336% compared to the FBR circuit (Hsieh et al. 2016). However, SSHI circuits encounter startup issues in environments with low or variable amplitude vibrations, making them unsuitable for many railway applications. As an alternative, the synchronous electric charge extraction circuit (SECE), which operates independently of load, has gained popularity in PVEH systems for its improved energy extraction efficiency (Li et al. 2022a, b, c). The SECE circuit has been implemented in broadband and random vibration-based PEHs, bypassing the traditional rectifier bridge structure and providing stable DC output for railway applications. Nevertheless, in PMEH systems, where there is high coupling, the SECE circuit can excessively amplify mechanical damping, reducing the deformation of piezoelectric stacks and leading to lower power output. The net result is a failure to improve energy extraction efficiency compared to PVEHs. To address this, Morel (Morel et al. 2019) introduced an N-SECE circuit, specifically for highly coupled or low-damped PEHs, which enhances energy extraction efficiency by 257% over traditional SECE circuits (Figs. 20, 21).

In addition to these challenges, the load impedance in the railway environment can vary over time, making impedance matching crucial for maximizing harvester efficiency (Ottman et al. 2003). Maximum power point tracking circuit (MPPT) is a widely used impedance-matching technology that adjusts the duty cycle to ensure optimal load adaptation. An MPPT algorithm designed for the PEH system, as

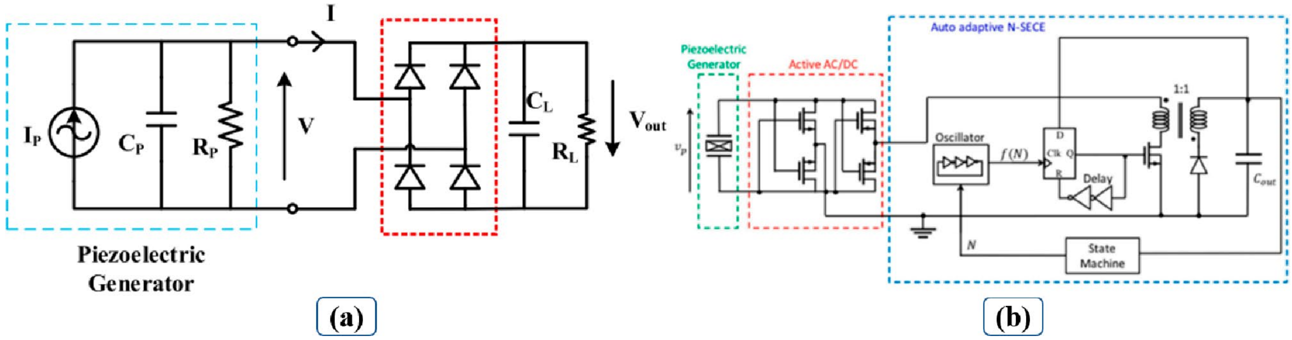

Fig. 20 (**a**) full-bridge rectifier (FBR) circuit (Li et al. 2022c), (**b**) synchronous electric charge extraction (SECE) circuit (Morel et al. 2019)

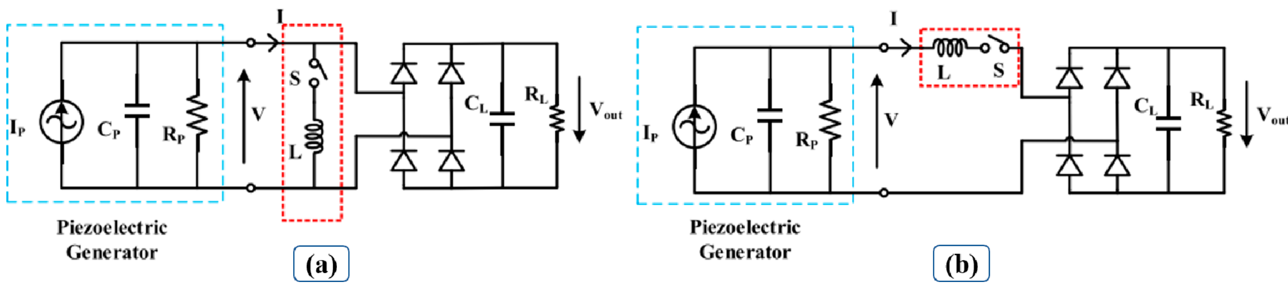

Fig. 21 Switch-based rectifier (SSHI) circuit: (**a**) Parallel-SSHI, (**b**) Series-SSHI (Li et al. 2022c)

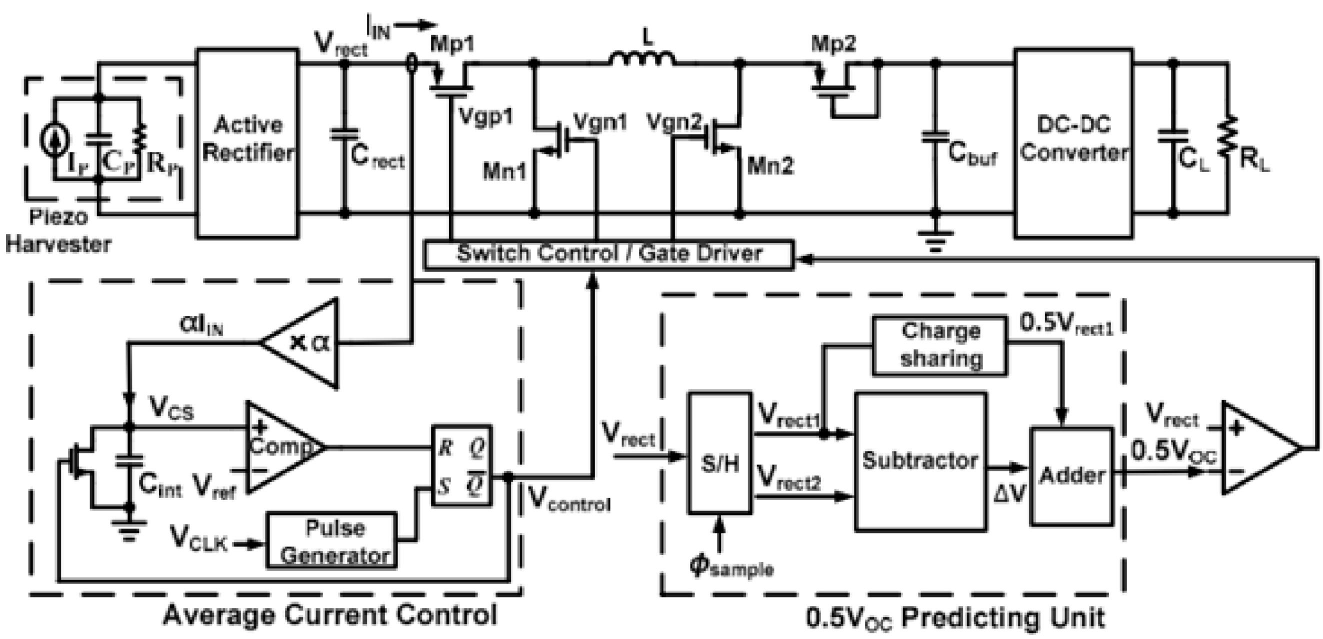

Fig. 22 Maximum power point tracking (MPPT) circuit (Hu et al. 2017)

proposed by Hu (Hu et al. 2017), demonstrated a voltage conversion efficiency of 98.7% and an energy conversion efficiency of 73%, highlighting the potential of this technology for improving the performance of piezoelectric harvesters (Figs. 22).

4.3 Transmission and communication technology

Data transmission and communication equipment are critical components of most railway health monitoring systems. Wireless sensors powered by PEHs aim to transmit data without the need for wired connections, leveraging wireless communication technologies (Hidalgo-Leon et al. 2022). This reduces wiring and maintenance costs while enhancing the system's flexibility and adaptability to diverse environments (Sun et al. 2024). The data gateway aggregates data from multiple sensors and transmits it to a more distant data processing center via cellular networks or IoTs. Data repeaters are employed to extend the communication range, ensuring the signal covers a large area, especially in complex terrain or remote railway regions (Egea-Lopez et al. 2005). Although the data gateway can be located further from the track/sensors, where it is more likely to have a reliable power supply (e.g. battery/solar), PEHs-powered sensors must generate sufficient power to process the data they collect. This may involve on-board-edge computing and/or data transfer to the gateway. The choice of communication strategy is influenced by factors such as power requirements, transmission distance, data rate, communication time, and implementation cost (Elson and Römer 2003; Zahid Kausar et al. 2014). The communication technologies widely used in sensors are divided into wireless personal area networks (WPAN), low power wide area networks (LPWAN), and wireless local area networks (WLAN), as shown in Table 5. Based on power consumption and coverage, WPAN and LPWAN are more suitable for communication transmission, with LPWAN particularly advantageous for large-scale data transmission. Even sensors with limited power supply or relatively low power consumption can use LPWAN for various sensing applications (Dirnfeld et al. 2020).

The primary technologies within LPWAN include LoRa, Sigfox, and NB-IoT. LoRa, an emerging data transmission technology, enables communication from terminal nodes to base stations, offering robustness with transmission distances reaching hundreds of kilometers. There is the potential for LPWAN solutions like LoRa to become the preferred choice for wireless sensor data transmission in the future, particularly for self-powered sensors (Liu et al. 2019). Despite certain limitations, WPAN and WLAN remain integral to intelligent railway monitoring systems. WLAN excels in providing high-speed data transmission over short distances, such as between data gateways and repeaters, while WPAN is better suited for visualizing monitoring data at local levels.

4.4 Multi-mechanism coupling harvesting

To enhance power generation in harvesters for railway applications, hybrid harvesters that combine piezoelectric and electromagnetic mechanisms offer a potentially attractive solution. These hybrid harvesters may consist of multiple generators with different conversion mechanisms or a single system capable of harvesting multiple forms of energy. The trend toward hybrid harvesters is growing due to their enhanced output efficiency compared to traditional PEHs, with these mechanisms, particularly piezoelectric and electromagnetic, being developed to optimize energy efficiency.

As reported by Tadesse (Tadesse et al. 2009), electromagnetic harvesters are effective at low frequencies, while piezoelectric harvesters excel at higher frequencies. The combination of these two mechanisms allows for more effective harvesting of the vibration energy prevalent in railway environments. A hybrid harvester designed by Sang (Sang et al. 2012) demonstrated an 81.4% increase in power output compared to single-mechanism harvesters, highlighting the potential of hybrid systems in complex environments. To enhance energy conversion efficiency, Li et al. (Li et al. 2024) integrated a piezoelectric harvester with an electromagnetic counterpart. Experimental results showed the hybrid harvester generated a maximum power of 3.276 mW at a frequency of 9.5 Hz. Hybrid harvesters can also be designed to exhibit nonlinear behavior, improving their ability to achieve peak power across a broad frequency range (Xia et al. 2020; Ahmad and Khan 2021). On their own, PEHs are often more effective at converting high power density from the same vibration sources. The total power output of hybrid harvesters that integrate electromagnetic and piezoelectric mechanisms tends to increase as the system reaches steady-state operation and higher amplitudes (Xia et al. 2019). Nonlinear configurations such as bi-stable (Sun et al. 2023; Dong et al. 2024), tri-stable (Wang et al. 2020b; Zou et al. 2021), and quad-stable (Ju et al. 2021) PEHs are particularly suited for environments with broadband excitation, as shown in Fig. 23. Unlike monostable structures, multi-stable structures feature multiple magnets at the ends of the cantilevers, creating potential

Table 5 Comparison of WPAN, LPWAN, and WLAN

	Technical examples	Coverage range	Power consumption	Data rate	Applications
WPAN	Bluetooth Zigbee	Short range, from a few meters to several tens of meters	Low power consumption, suitable for short-term monitoring	Medium data rate, with Bluetooth operating at 1 Mbps to 3 Mbps and Zigbee at 250 kbps	Data gateway and repeater, wireless sensor
LPWAN	LoRa Sigfox NB-IoT	Long range, from a few kilometers to several tens of kilometers	Ultra-low power consumption, suitable for long-term monitoring	Low data rate, ranging from several kbps to several hundred kbps	Long-term monitoring, smart railway system
WLAN	Wi-Fi	Medium range, from several tens of meters to a hundred meters	High power consumption, unsuitable for monitoring applications	High data rate, from tens to hundreds of Mbps	Wireless network, App data reading

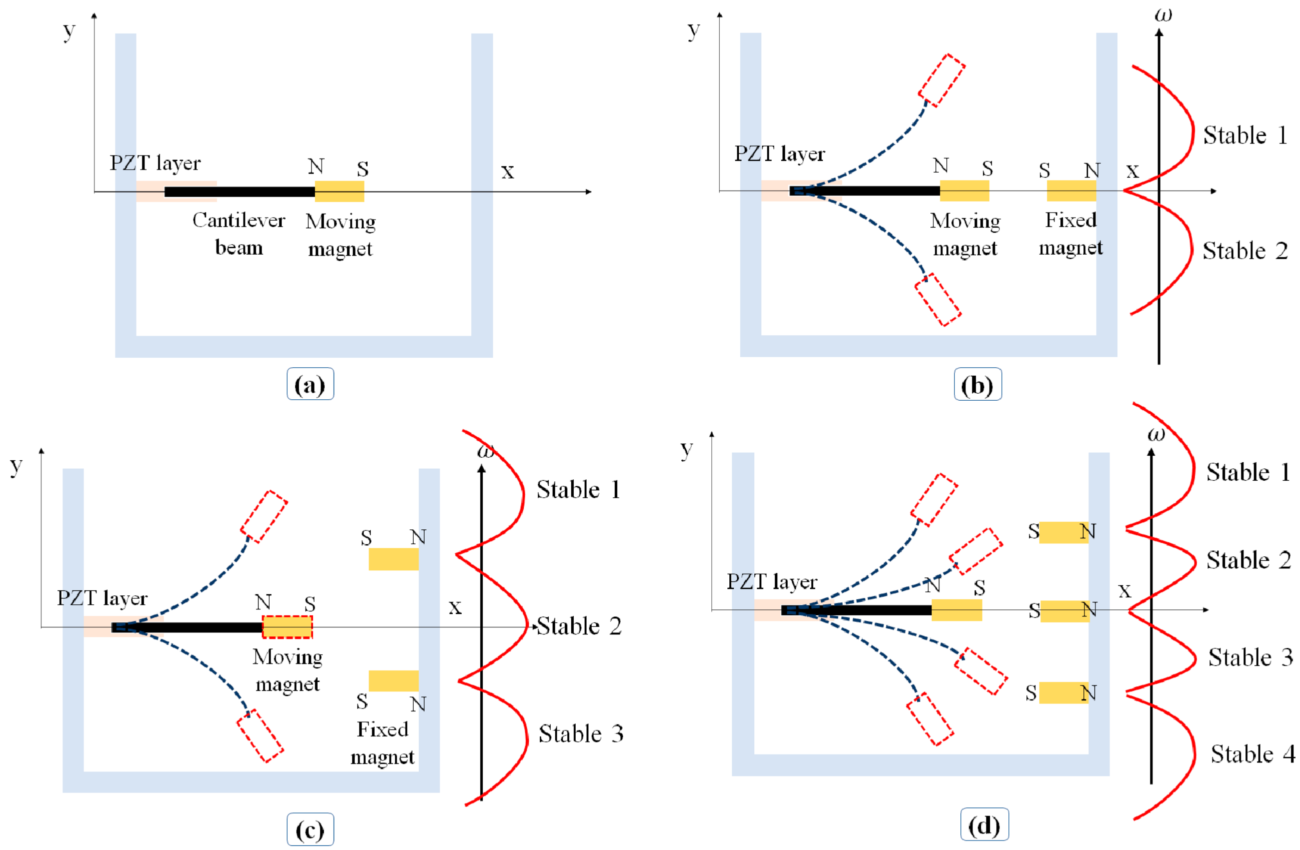

Fig. 23 Typical multi-stable structures of PVEH including (**a**) mono-stable, (**b**) bi-stable, (**c**) tri-stable, and (**d**) quad-stable

wells through the nonlinear forces of magnet attraction and repulsion. The number of potential wells correlates with the system's steady-state. Motion between these wells can induce greater displacement in the cantilever, resulting in higher power output. However, if the excitation frequency or amplitude is insufficient, only intra-well motion occurs, typically generating lower power (Daqaq 2012). In the fluctuating conditions present in the railway environment, the efficiency of a bi-stable system may be low, whereas tri-stable and quad-stable systems have the potential to initiate inter-well motion under weaker excitations, thereby enhancing output performance (Kim and Seok 2014).

4.5 Reliability and maintenance

In the design of PEHs, the primary focus is on energy extraction efficiency and output power. However, the harsh environmental conditions along the railway can significantly impact the longevity of these devices. The constant mechanical motion and stress concentrations during train operations can further compromise their reliability.

One approach to mitigate motion amplitude and enhance reliability is the use of structures such as cymbal and bridge-type force amplifiers. These designs have shown promising power outputs by effectively eliminating stress concentrations. Nevertheless, the low tensile strength of piezoelectric materials raises concerns about their durability. For example, Zhao et al. (Zhao et al. 2012) reported that harvesters using bridge-type force amplifiers failed when peak stress exceeded 30 MPa. Similarly, Kim (Kim et al. 2004) observed the appearance of a linear crack in a piezoelectric bimorph cantilever within just 2–3 min of operation.

PZT stacks, commonly used in these harvesters, are subject to both tensile and compressive stress during operation. Although piezoelectric ceramics have low tensile strength, which can drastically reduce the service life of PEHs, they exhibit significantly higher compressive strength (>600 MPa). To address this, pre-compressing piezoelectric ceramics to alleviate tensile stresses has become a strategy to enhance the durability and longevity of piezoelectric harvesters (Kuang et al. 2021).

4.6 Future directions

Based on the above review and discussion, it is considered that the PEHs need to be further improved in terms of efficiency, integrability, practicality, and durability for future engineering applications.

(1) **Integration of Artificial Intelligence (AI) for energy optimization**: Future PEH systems could benefit from the integration of AI to dynamically optimize both energy harvesting and storage, adapting to real-time environmental conditions and sensor demands. AI could enable the system to predict energy consumption needs and adjust harvesting parameters, such as resonance tuning, in real-time to enhance overall efficiency.
(2) **Scalable energy harvesting systems with modular designs**: The future of PEH systems may involve modular designs that enable scalable energy harvesting solutions. These systems could be tailored to meet the specific power requirements of various components of railway infrastructure, from the track to the train, while ensuring integration with existing systems.
(3) **Coupled dynamics of PEHs and vehicle-track system**: To ensure the safety of railway operations, it is essential to understand the coupling dynamics between the railway system and energy harvesters. For PEHs, the location of installation, whether onboard the vehicle or trackside, can impact the dynamics of the vehicle-track system.
(4) **Development of self-healing piezoelectric materials**: To enhance the durability of PEHs, research into self-healing piezoelectric materials has the potential to improve their longevity. By incorporating self-healing polymers or materials capable of recovering from mechanical damage, PEHs would be better suited for long-term deployment in demanding environments such as railways.

5 Conclusions

This paper provides a review of PEH solutions within the railway sector, focusing on their design, optimization, and implementation for various energy types, including vibration, mechanical, friction, sound, and wind energy. The review emphasizes the structural optimization and practical implementation of PEHs, highlighting their potential for self-powered systems. The main findings are as follows:

1. Enhancement of Frequency Band and Performance: Multi-DOF and multi-stable PEHs have the potential to broaden the frequency range and improve overall performance. Techniques such as adjusting resonant frequencies through varying mass blocks or array cantilevers offer promising solutions. Additionally, multi-stable hybrid harvesters that integrate both piezoelectric and electromagnetic effects exhibit nonlinear behavior, which can enhance peak power generation and enable broadband energy capture. However, their practical application is limited by challenges such as inter-well vibration, which requires further investigation for real-world deployment.
2. Complexity of Self-Powered System Circuits: The inherent complexity of self-powered system circuits influences the design of piezoelectric harvesters. The synchronous electric charge extraction (SECE) circuit has gained popularity for its effectiveness in broadband and random vibration environments. Additionally, the N-SECE circuit, specifically designed for highly coupled Piezoelectric Mechanical Energy Harvesters (PMEHs), addresses variations in load impedance in complex environments. Future research should focus on optimizing performance based on random impedance variations to enhance the efficiency and adaptability of these systems.
3. Integration of energy harvesting with communication protocols: Wireless communication technologies, such as RF and Bluetooth, are commonly used to facilitate real-time monitoring and data sharing between sensors and centralized systems. However, challenges such as signal interference, limited bandwidth, and the energy consumption of communication devices must be addressed to enhance the overall performance and scalability of these systems. Future research should focus on improving the integration of energy harvesting with communication protocols, ensuring continuous, low-power, and efficient data transmission in dynamic and remote railway environments.
4. The demanding and often fluctuating mechanical conditions within railway environments significantly impact the durability and operational lifespan of energy harvesters. Future research should focus on optimizing material durability and structural reliability to improve the lifespan and safety of PEHs, taking into account typical on-site railway conditions. Meanwhile, the efficiency, integrability, practicality, and durability issues of PEHs in the railway industry need to be further explored in the future.

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Author contributions R.Z. wrote the initial draft of the manuscript. P.A. conducted the literature review and contributed to the analysis of piezoelectric energy harvesting principles and applications. D.P.C. and W.H. provided critical insights into the challenges and future research directions, and contributed to the interpretation of the findings. G.J. supervised the project, contributed to the conceptual framework, and reviewed the manuscript for important intellectual content.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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