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Review article

Advancements in energy harvesting techniques for sustainable IoT devices

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ABSTRACT

This paper reviews the energy harvesting techniques for sustainable Internet of Things (IoT) devices. With the passage of time, more things and objects are connected to the internet, paving the way for the development of IoT. The term IoT describes the network of everyday devices that are interconnected together and exchange data via the Internet. Wireless sensors are included in IoT devices to collect data in an accurate and useful way for process monitoring and activity control. The batteries that run these wireless sensors have a limited lifespan, rapidly drain, and need replacement. The replacement and maintenance process is costly; thus, smart energy management is essential for IoT devices to be energy-efficient. Therefore, energy harvesting is a promising method to supply such low-powered IoT devices by utilizing various energy resources. This energy can be harvested from different environmental, mechanical, chemical, and bioenergy sources, eliminating battery dependence. First, this review explains the importance of energy harvesting techniques for powering IoT devices, followed by IoT energy harvesting. Then it explains different energy harvesting techniques, followed by a table showing the analysis of these techniques. After that, this review explains the cost of these harvesters. Finally, there are future recommendations and conclusion, which shows some challenges that IoT energy harvesting faces that need to be addressed to grow sustainable IoT devices.

1. Introduction

The ITU (International Telecommunications Union) released its initial report on the IoT fifteen years ago [1]. To establish a new dynamic system of networks, the Internet of Things (IoT) paradigm was initially described as a "new dimension added to the realm of ICTs (information and communication technologies) which enables forming connections to anyone & anything, anytime & anywhere" [1]. The development of the IoT has opened up limitless possibilities to enhance the intelligence and efficiency of the world around us. It has the ability to revolutionize each aspect of life completely. The rise of IoT devices in diverse applications is a great testament to this assertion. These applications include smart cities [2], robotics, intelligent agriculture [3], implants, wearables, health monitoring systems [4], environmental monitoring, traffic monitoring, smart buildings, etc. [5,6]. It is now regarded as one of the most significant technological advancements of the twenty-first century, with applications across various industries, including energy, transportation, smart buildings [7], civil infrastructure, defense, manufacturing [8], and production, the pictorial representation of a smart city is shown in Fig. 1 [2]. According to expert predictions in 2020, there will be over 22 billion Internet of Things (IoT) devices on the Internet and interacting with one another by 2025 [9].

The sustainable growth of the IoT devices is important. It could be made possible by using environmentally friendly materials, eliminating toxic materials, and lowering carbon footprints. Moreover, using energy harvesting technology eliminates the need for batteries for IoT devices

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[10–13].

IoT systems also face several challenges, which include security, reliable data transfer, interoperability, and energy consumption. IoT devices cannot use current security protocols like Advanced Encryption Standards and Data Encryption Standard because of their heterogeneity and resource constraints [14–16]. However, the most significant challenge is efficient energy management [17]. For the IoT network to function properly, each active component needs to use a specific amount of energy. Despite using limited energy resources [18], it has recently seen a major rise in the overall amount of data generated by IoT [19,20]. As a result, via the wireless channel, the batteries for communicating objects rapidly drain and regularly need to be replaced. Therefore, energy harvesting is a promising method to supply such low-powered IoT devices by utilizing various energy resources [21]. Energy harvesting is the process of obtaining energy from diverse external sources and transforming it into electrical power (for IoT devices). With the use of this technology, the need for frequent battery maintenance and replacement can be significantly reduced, producing more long-lasting and reliable solutions [22].

As these batteries threaten the IoT's rapid development, the energy harvesting techniques for the IoT devices are currently the hot topic. IoT devices usually run on batteries, which drastically reduces their lifespan. These IoT sensors require power in order to exchange data. The primary challenge of these devices lies in maintaining them and managing their power supply for the excessive data sets. As large datasets and energy-demanding IoT devices are expanding, effective energy management is crucial [23,24].

Since 2017, the use of artificial intelligence (AI), big data, and blockchain-integrated IoT has grown significantly [25]. Most enclosed systems, like cameras, speakers, sensors, etc., are easily controlled and connected to the internet. Many of these devices are small, wireless and rely on sensors to collect and transmit data. They are often placed in hard to reach locations (i.e., remote areas or embedded in structures), accessing them for maintenance and battery replacement can be challenging. Batteries are not a good option for them because it is costly, difficult, and labor-intensive to install batteries in small sets. In light of these conditions, developing an energy harvesting system utilizing various resources is an efficient technique that can help address problems with IoT-controlled device powering [26].

Since energy harvesting technologies offer more power to IoT systems, certain factors like size, end-user device type, and IoT applications must be considered to satisfy their potential for integration with them. The performance requirements for each IoT system will vary depending upon the wireless communication technology used. Where one of the most important factors is the energy consumption. A unified energy-model approach is required since the literature does not adequately characterize these technologies on the basis of their energy consumption. Energy harvesting is one of the popular methods for enhancing IoT sustainability. According to the existing literature, the energy generated through the energy harvesting may not always be adequate for IoT communication technologies due to the limited and irregular behavior of the energy sources for energy harvesting. Therefore, incorporating energy harvesting into the wireless communication systems while maintaining system performance is important [27,28].

There are various energy resources. Solar energy is one of the most widely used in energy harvesting technologies. IoT devices generate energy from solar radiation and use it for powering themselves. These devices also generate energy by using mechanical energy, i.e., piezoelectric materials, which convert the motion into electricity. Thermoelectric energy harvester utilizes a temperature gradient to convert that into electricity by utilizing thermoelectric materials. IoT devices are also able to harvest energy through nearby radio frequency signals [28]. By using these technologies, the IoT devices run for a longer period without the need for an external power source. There are many other energy harvesting techniques as well which are discussed in this review.

Energy harvesting for IoT devices has been extensively researched in the literature, with a primary focus upon the technical, implementation aspect, optimizing energy collection and different energy resources. The objective of this study is to identify advancements and different energy harvesting techniques available from different energy resources, their literature review, advantages, disadvantages, cost analysis of these techniques, and to assist future researchers and scientists in this field, paving the way for future direction. The review is organized as follows. Section 2 of this review highlights the importance of energy harvesting for IoT devices. This section highlights the battery's limitations as a power source. Section 3 presents various energy harvesting techniques that harvest energy from various sources for powering IoT devices. These techniques include ambient energy harvesting (aeroelastic, solar, sound, radio frequency, wind, and thermal), mechanical energy harvesting, chemical energy harvesting, and bioenergy harvesting. We classified these techniques according to the sources. This section also contains a Table that analyzes each energy harvesting technique. Second 4, then delve into the cost of the energy harvesters. Finally, Section 5 presents future recommendations and conclusions.

2. IoT energy harvesting

Energy harvesting is the process of transforming readily available environmental energy into useable electrical energy. This offers an appropriate method to power different loads continuously. Energy sources can be obtained from the environment (ambient) and external dedicated sources. Ambient energy sources, including solar, radio

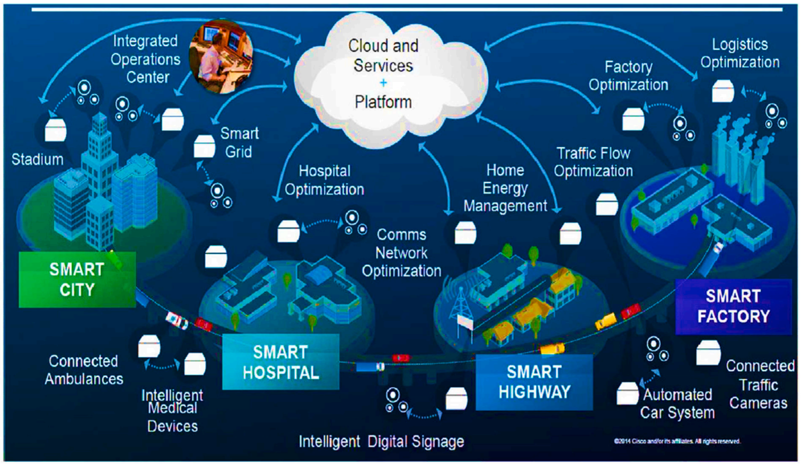

Fig. 1. Pictorial representation of a smart city [2]. Copyright 2018, The Institution of Engineering and Technology (IET).

frequency, thermal, aeroelastic, sound, wind, hydro, and motion, are more accessible and naturally available from the environment. The classification of various energy sources for powering IoT devices is shown in Fig. 2.

There are numerous drawbacks associated with the utilization of batteries as a power source for wireless devices. The occurrence of leakage leads to the depletion of battery power even during periods of inactivity. Additionally, the impact of temperature on the batteries' ability to function effectively restricts the range of applications for these devices, as extreme temperatures can result in power and capacity losses [29]. The weight and dimensions of batteries directly influence their capacity. Moreover, the environmental implications are of great significance due to the presence of toxic and hazardous chemicals in batteries, thereby making their disposal a more challenging task [29,30]. This is why modern wireless sensors are engineered with energy-harvesting components, thereby completely obviating the need for batteries.

Fig. 3 shows the four phases associated with the energy harvesting process. The availability of energy resources is the first phase (which includes energy from the environment, mechanical energy, chemical energy, or bioenergy). The second phase involves energy conversion. The harvester (or transducer) detects and converts the energy into usable electrical energy. The third phase includes energy storage, which is stored in batteries or supercapacitors. This phase is also associated with the control unit and power management. And the final stage involves energy consumption, which IoT devices consume [31]. There are two main architectures, "Harvest Use" and "Harvest Store Use", that result from the ability to consume energy immediately when it is collected or stored for later use, respectively [32].

Many energy harvesting approaches have been presented in recent years to address the problems associated with battery-powered electronic devices. Energy harvesting techniques have many advantages; they are economical and require less frequent maintenance because they are simple to fabricate; when compared with battery-based systems, they produce fewer carbon emissions; biodegradable [33], bio-compatible and pollution-free [34], green materials (substrates) can be used with them; and they integrate easily with widely accessible wireless communication networks [33].

We can also use hybrid energy harvesting techniques to power IoT devices. It means the integration of multiple energy sources. Combining multiple energy sources reduces the deficiencies of a single energy source. For example, solar energy is not readily available at night; however, we can use radio frequency radiations with it that can easily operate without light [35].

Section 3 below explains various energy harvesting techniques from different energy resources for powering IoT devices, along with the work done by the researchers in this field.

3. Energy harvesting techniques for IoT devices

This section-3 delves deep into the various energy harvesting techniques that can be utilized to harness energy, as shown in Fig. 2.

3.1. Ambient energy harvesting

3.1.1. Aeroelastic energy harvesting

Flow-induced structure vibrations have drawn a lot of attention from many researchers in recent years because of the potential source of energy harvesting for the Internet of Things (IoT) devices [36,37]. The ability of these harvesters to convert fluid flow energy, which appears as structural vibrations, into usable electrical energy for powering the IoT device makes them an excellent example of the fluid-structure interaction. In aerospace engineering, these harvesters have a lot of applications. The disadvantages of conventional batteries are their weight, high maintenance costs, and sometimes extremely difficult maintenance (such as on high-altitude platforms) [38,39]. Due to this, an aerospace vehicle must have a smart structure that can harness energy from its surroundings, utilize it for powering wireless sensors, and send data to a ground-based station through a TTC subsystem [40].

Elahi et al., in their research, modeled a piezoelectric aeroelastic energy harvester. It is based on fluid-structure interaction, an essential field of research for creating innovative energy harvesting solutions. This energy harvester utilizes Limit Cycle Oscillations (LCOs), which

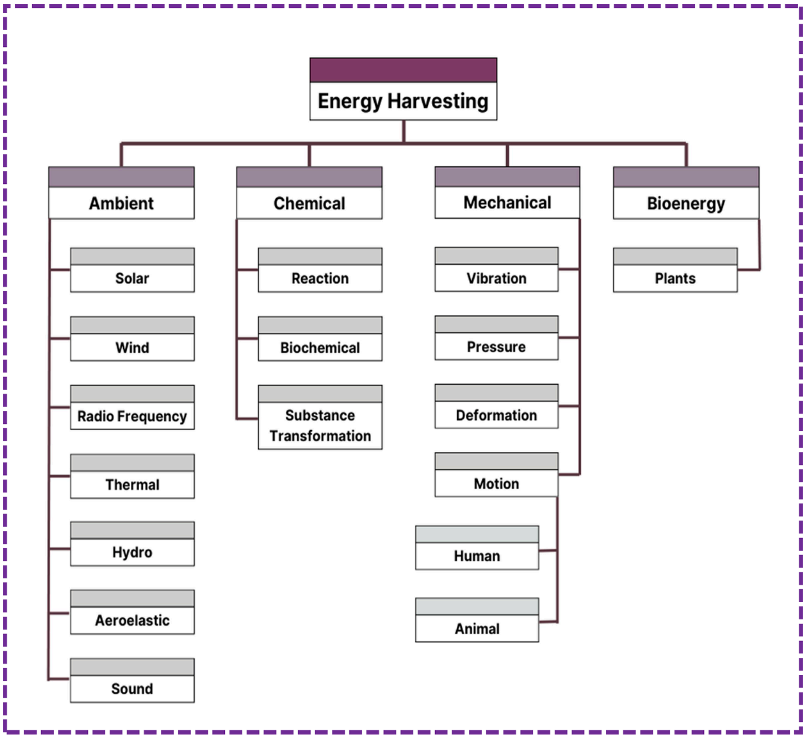

Fig. 2. Flowchart showing the classification of the sources from where the harvested energy comes for powering IoT devices.

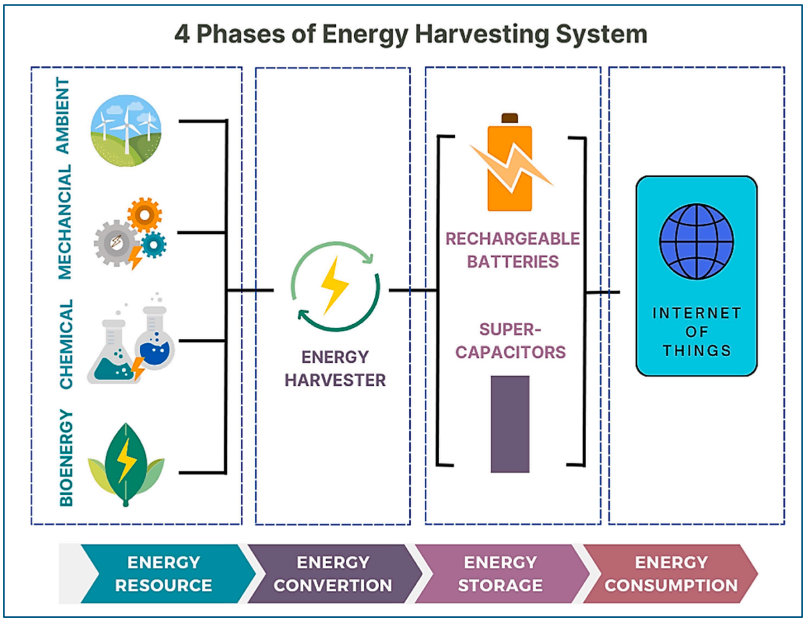

Fig. 3. Energy harvesting system block diagram.

emerge after flutter velocity. This harvester is designed by using PZT-5A and $BaTiO_3$ piezoelectric materials. These materials are utilized by the proposed harvester to power nano and microelectronics IoT devices. This harvester generates an output power of 0.55 mW [41]. Fig. 4 [41] shows a schematic illustration of a proposed piezoelectric aeroelastic energy harvester. It consists of a wing that is attached to a control surface i.e., a flap. Energy harvesting occurs when the airfoil is exposed to airflow, and LCOs are transferred to a piezoelectric patch after fluttering velocity. Another interesting field to power IoT devices is galloping-based aeroelastic energy harvesting [42,43]. The power output produced by the galloping-based aeroelastic energy harvester is shown in Table 1, which compares different fluid-interaction-based piezoelectric energy harvesters that potentially power the Internet of Things.

3.1.2. *Solar energy harvesting*

Solar energy stands out as a highly abundant and renewable resource on our planet, with an energy production of about 173 × 1012 kW [51]. Approximately 3.4 × 1024 J of energy reaches the earth's surface each year, which is 7000–8000 times more than the world's annual primary energy consumption. There are numerous applications of this light energy. The solar cells, also known as the photovoltaic cells, are used to convert sunlight into electricity [52]. Solar light is used for outdoor environments, while artificial lights are used for indoor environments. Artificial energy harvesting efficiency is one-third that of solar energy harvesting efficiency. Solar energy has an output power density of about 100 mW/cm^2 during the day and zero energy at nighttime [53].

Table 1
Comparison of different aeroelastic energy harvesters' power.

Authors	Type	Mechanism	Power (mW)	References
Daqaq, M.F	MFC-M8514-P2	Galloping	0.22	[44]
Sirohi, J & Mahadik, R	PSI-5H4E	Galloping	50	[45]
Akaydin et al.	PZT-5A	Vortex-Induced Vibration (VIV)	0.1	[46]
Naseer et al.	PZT	Vortex-Induced Vibration (VIV)	23	[47]
Abdelkefi et al.	QP 10N	Flutter	2.2	[48]
Tsushima et al.	PZT	Flutter	0.003	[49]
Elahi et al.	PIC 255	Flutter	10.8	[50]

Although solar energy is unpredictable and its conversion efficiency is influenced by seasonal variations, ambient temperature, weather, and day-night cycles, it can be modeled to help develop appropriate strategies for ensuring that electronic devices have a continuous power supply [54–58].

The most common means of harvesting light energy is photovoltaic, often known as the photoelectric effect. There are various types of photovoltaic (PV) cells available in the market that set them apart from other construction materials. Because of the different materials, they have different costs and efficiency. The simplest of them is a silicon-based PV cell. These silicon-based PV cells have three categories:

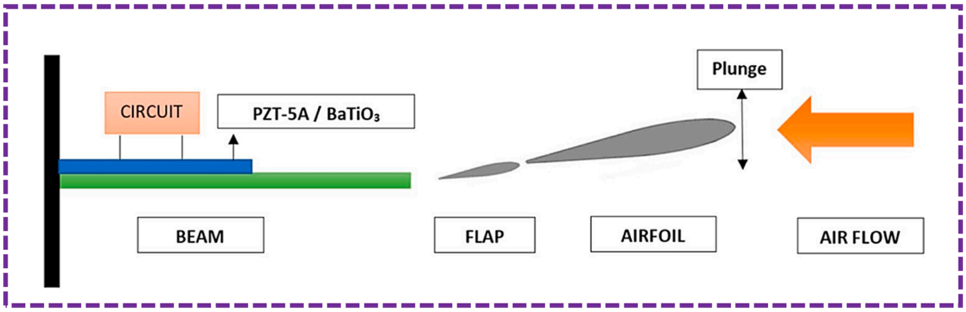

Fig. 4. Schematic diagram of piezoelectric aeroelastic energy harvester proposed by Elahi et al. [41]. Copyright 2019, Elsevier.

amorphous, mono-crystalline, and polycrystalline [31]. Although polycrystalline cells are less expensive, their efficiency is just 20 %. However, compared to polycrystalline, monocrystalline has higher rates and approaches 25 % efficiency. The cheapest of them is amorphous, but its efficiency is much lower than the two.

The criterion that is used to compare their performances is efficiency, defined as the “Ratio of power output to incoming power of light under $100mW/cm^2$ illumination” [59]. A standard photovoltaic cell has two layers of semi-conducting material, often silicon, each doped with P and N-type material [60]. The N-type layer is positioned to absorb light. Photons are absorbed by the material upon light strike, allowing electrons to flow through the PN junction. The P-type material has holes filled by these electrons. The unused electrons are returned to the N layer, creating a current flow surrounding the PV cell. This process efficiently transforms light energy into electrical energy. The schematic illustration of this photovoltaic energy harvester is shown in the Fig. 5 [31].

Light energy harvesting has been utilized in various low-power Internet of Things applications, from large-scale agriculture to smart homes [61]. The Waspmote by Libelium, the most commonly utilized IoT sensor node, consists of a solar panel providing 12 V to 500 mA of energy supply [62]. Solar Biscuit is another popular solar-powered sensor network system with a (5 × 5)cm solar panel and 1 Farad supercapacitor [63]. Spachos, P. & Mackey, A [64] proposed a circuit for harvesting light that can be used to power the BLE (Bluetooth Low Energy) beacon. Low-cost BLE beacons are used to communicate basic contextual data, i.e., advertisement, location, and acknowledgment, across various IoT nodes. There are differences in light intensity between outdoor and indoor environments. Circuits that harvest light are more effective outside but produce less amount of energy indoors. Masoudinejad et al. [65] in their research proposed an indoor harvester utilizing photovoltaic cells with various techniques for adjusting light intensity. 400 μW of output power can be obtained with varying light densities. We can construct effective energy-autonomous devices with PV technology combined with adequate energy storage, suitable circuit design, right dimensioning, and power consumption optimization [66–69].

3.1.3. *Sound energy harvesting*

Sound energy harvesting has a lot of potential, as it causes noise reduction and is converted into electricity for powering nano/micro-sensors for IoT, environment monitoring, structural monitoring, and many other applications. Due to inherent frequency mismatches between regular sound wave frequencies, there may be a significant energy loss during this energy harvesting. Mostly sound energy harvester research focuses on piezoelectric nanogenerators [70,71]. A TENG based on the triboelectric effect is created for the purpose of harvesting mechanical vibration energy [72,73].

Yang et al. [74] designed a thin-film nanogenerator based on triboelectrification to harness acoustic energy from the surrounding environment, the schematic illustration of this nanogenerator is shown in Fig. 6(a). It consists of a thin film of polytetrafluoroethylene and aluminum electrodes. The nanogenerator converts the sound energy into electric energy through triboelectric transduction. It generates a maximum power output of about $60.2mW/m^2$, directly lighting 17 commercial LEDs with a current density of about $1.6mA/m^2$. Additionally, this nanogenerator can function as an autonomous active sensor to locate an acoustic source with an inaccuracy of <7 cm. This technology is adaptable, portable, and cost-effective for capturing acoustic energy from the environment. It is used in military surveillance, sensor networks, infrastructure monitoring, and noise reduction in the surrounding environment. Zhou et al. [75] designed a (BAEH) Bi-stable Acoustic Energy Harvester to harvest noise energy. This harvester consists of a fixed magnet, a moveable magnet, a flat plate (at the free end), a curved plate, and a piezoelectric cantilever beam, as shown in the Fig. 6(b). The flat plate will experience dynamic forces from the incoming and reflecting waves on its front and back sides. This will cause the plate to oscillate and snap through between equilibrium states, producing a large output. Because the harvester can achieve the coherence resonance, it can produce a large output. At 95 dB, output voltage of 60 mV is achieved. Cui et al. [76] fabricated a sound-driven (TENG) triboelectric nanogenerator made of mesh membrane and (PVDF) polyvinylidene fluoride nanofibers, as depicted in the Fig. 6(c). It can operate stably in a wide frequency range of about 50 Hz - 425 Hz. It can charge at a rate of 61 μC/s and has an output current of 0.45 mA. Additionally, the TENG vibrated 100 million times for seven days without showing any signs of output signal decay.

3.1.4. *Radio frequency energy harvesting*

A few nW/cm^2 of ambient radio frequency (RF) radiations opens up the potential for battery-less, sustained WSNs’ with limited functionalities. These battery-free WSNs can be installed in challenging and remote environments for monitoring and sensing applications [77]. Sources of RF signals, which fall between the frequency range of 3 kHz to 300 GHz, include satellite and radio stations, digital multimedia broadcasts, and wireless internet. Rectifier circuits and antennae are used to convert these signals into electric power. This harvester converts the incident RF energy into DC energy, powering the battery-less WSNs. The harvester consists of an antenna, matching network, RF-DC converter, and output load, as shown in the Fig. 7(a) [78]. After reviewing previous research in this field [79–81], it is shown that RF energy harvesting is optimal for low-power IoT devices.

Devices ranging in 15 m can receive power transfers wirelessly from an RF harvesting system [82]. These harvesting systems have attracted much attention due to the presence of radio frequency wave energy from cellular, radio stations, and WiFi. One problem for RF harvesters is their small power densities i.e., $0.2nW/cm^2$ to $1\mu W/cm^2$. In addition, the high-gain, small-sized antennas cannot produce sufficient power densities like other harvesters. The harvester’s output can only be kept at high power levels with the help of a high-gain antenna. High-power densities are also produced when RF harvesters are used close to RF towers. Conversion circuits and RF harvesters typically produce an output voltage of 1.8 V to 4.0 V and an efficiency of 10 to 30 %, using input power ranging from 30 dBm to 20 dBm [83].

Jose et al. [84] designed a three-chip radio frequency (RF) harvester

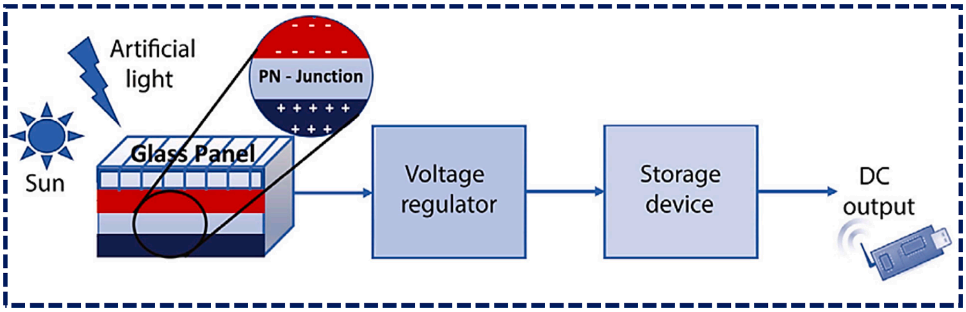

Fig. 5. Schematic illustration of the photovoltaic energy harvester [31]. Copyright 2020, Elsevier.

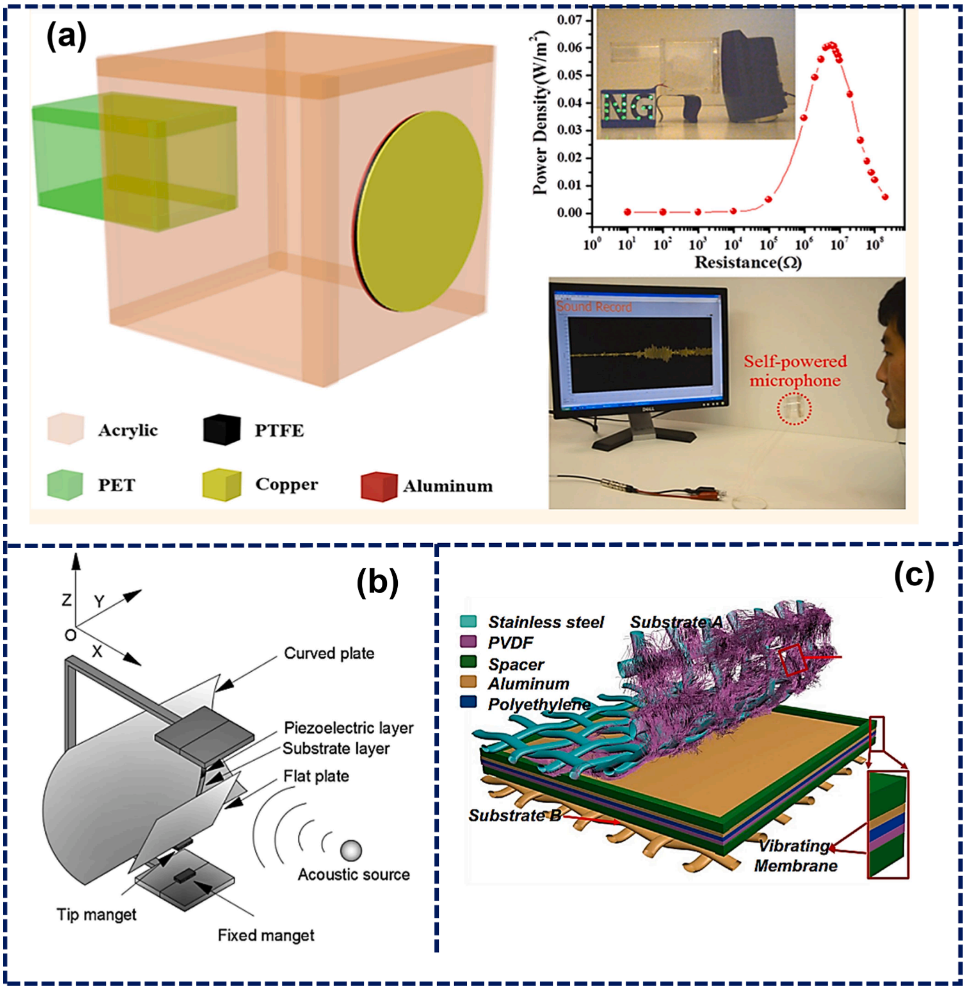

Fig. 6. (a) Thin-film nanogenerator based on triboelectrification proposed by Yang et al. [74]. Copyright 2014, American Chemical Society; (b) BAEH proposed by Zhou et al. [75]. Copyright 2017, Elsevier; (c) Schematic diagram of sound-driven TENG proposed by Cui et al. [76]. Copyright 2015, Elsevier.

utilizing a microcontroller and a DC-DC boost converter that are readily accessible commercially. The micrograph of the chip is shown in the Fig. 7(b). The third chip has low power measurement. This chip functions as a resistor emulation circuit (REC), converter, and RF-DC rectifier. RECs contribute to increased efficiency. This 1.5 × 1.5 mm chip was designed using CMOS technology. An IoT sensor node without batteries is fully powered by it. When radio frequency (RF) harvesters are utilized in conjunction with MEMS, they are known as RF-MEMS (Radio Frequency Microelectromechanical Systems). This concept was developed in the 1990's. However, in 2014 an advanced and effective RF-MEMS design was developed, which can be applied to future IoT applications [85]. A number of rectenna designs are put forward in [86] to power IoT applications and satellite health monitoring (SHM) systems. Bito et al. [87] proposed an mm-wave rectenna with inkjet printing for powering IoT devices, depicted in the Fig. 7(c). At 24 GHz, it produces an output voltage of 2.5 V DC while consuming an input power of 18 dBm. Multiband, high-gain antennas and beamforming for IoT applications can still raise power levels and efficiency.

3.1.5. Wind energy harvesting

Harvesting ambient wind energy is an efficient method for providing power to IoT devices. Modern IoT devices like remote sensors require extremely low power consumption [88]. Orrego et al. [89] utilized a flexible piezoelectric membrane having a novel orientation, that is, the inverted flag (i.e., inverted piezoelectric flag), to harvest the ambient wind energy. At 9m/s wind speed, 5.0mW/cm^3 of electrical power was recorded. Even under low wind speeds, i.e., 3.5m/s, the device produced sustainable power generation of 0.4mW/cm^3 appropriate for environmental wind energy harvesting. In addition, outdoor experiments were also conducted where ambient wind energy was harvested instead of batteries for powering a temperature sensor. These results provide new avenues for self-powered devices operating in low-speed and fluctuating ambient wind energy regimes. A schematic illustration of this wind energy harvester is shown in the Fig. 8.

Wind energy turbines can be classified into two types: Horizontal-axis Wind Turbines (HAWT) for the condition having constant wind direction, and the second one is Vertical-axis Wind Turbines (VAWT) for wind direction with the constant change. Wilson, R.E. and Lissaman, P.B [90] and Azevedo, J.A. and Santos, F [91] reported the theoretical power "P_T" produced by the wind turbine, which is shown in Eq. (1).

$$P_T = C_p P_0 = \frac{C_p \rho A v^3}{2} \tag{1}$$

Here "C_p" is turbine performance coefficient, "P_0" is maximum wind power available, "ρ" corresponds to air density, "v" is the speed of the wind and "A" is the turbine swept area.

Propeller and Pelton turbines are used to generate electricity from hydropower sources. For a high head and low flow rate, a Pelton turbine is utilized. While at a low head and high flow rate, a Propeller turbine is used. The hydro systems power "P_t" is expressed in Eq. (2) [91]

$$P_T = \rho g Q H \tag{2}$$

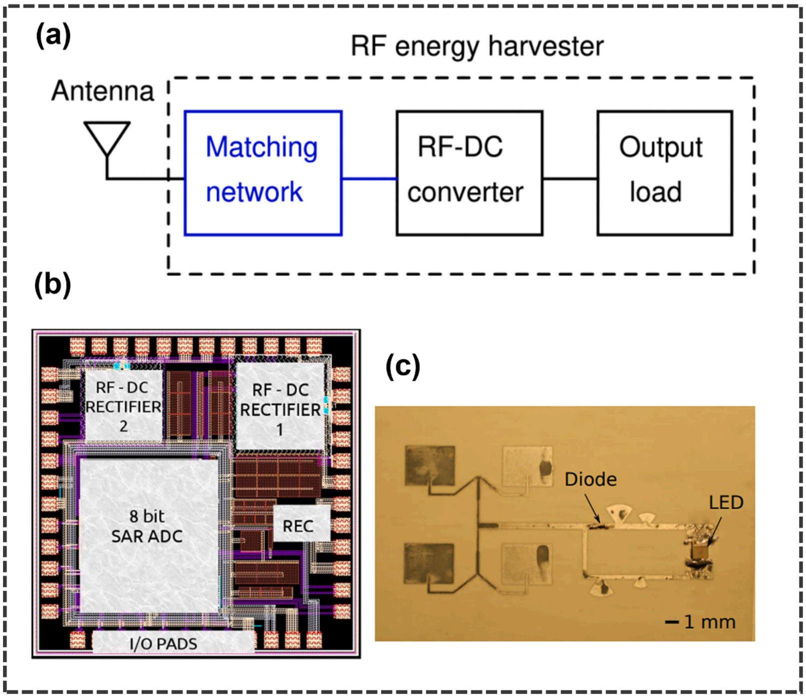

Fig. 7. (a) RF wave energy harvester block diagram [78]. Copyright 2023, IEEE (b) Micrograph of the chip proposed by Jose et al. [84]. Copyright 2015, IEEE; (c) Rectenna prototype proposed by Bito et al. [87]. Copyright 2017, IEEE.

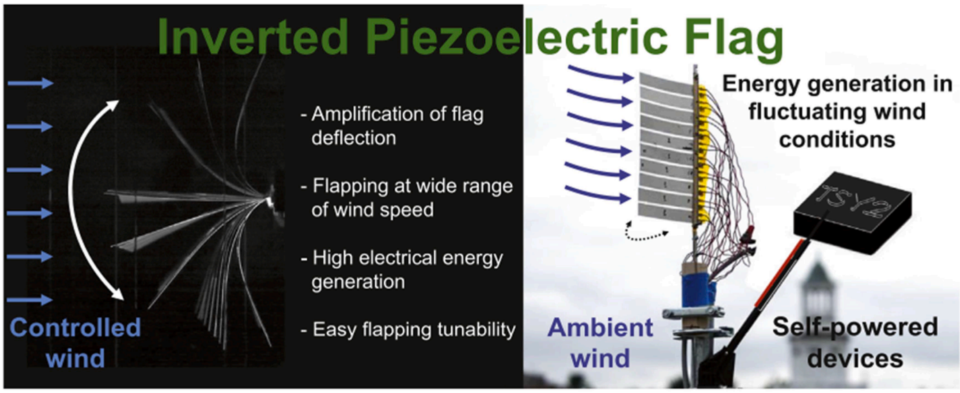

Fig. 8. Schematic illustration of wind energy harvester proposed by Orrego et al. [89]. Copyright 2017, Elsevier.

Here "ρ" corresponds to water density, "g" gravitational acceleration, "Q" is flowrate and "H" is head (height).

3.1.6. *Thermal energy harvesting*

The main source of thermal energy is heat and temperature variations. The most common and extensively utilized techniques for heat extraction are the thermoelectric and pyroelectric methods. The thermoelectric method immediately transforms the temperature difference into a usable energy form by utilizing the Seebeck effect. Applications for thermoelectric devices can be found both in terrestrial and in space. Numerous studies were conducted on energy harvesting using thermoelectric sources [92,93]. Pyroelectric energy harvesting converts waste heat energy into electric energy that may be used by battery-free IoT devices. It is appealing to obtain energy from the waste heat since it can transform fluctuations in temperature into electrical energy. Today, this approach holds great importance in IoT applications, i.e., healthcare, wearable technology, and in industries [94].

Thermal energy harvesters take different forms of heat, including heat from the sun, heat from exhaust gases, heat from internal resistance, human body heat, and heat flux, which can be transformed into electrical energy to power IoT devices. The system output also frequently produces heat as a byproduct, making the extraction of heat energy economical. Although thermal energy harvesting systems have a long lifespan and are reliable, their energy conversion efficiency is low [53].

In thermoelectric generators, the heating material is coupled with P and N type junctions. Carriers start moving from one connection to another when heat is applied to heating material. Due to the high thermal conductivity, silicon wafers and aluminum oxide are the most often utilized heating materials [60]. An increase in PN junctions around the heating material increases the amount of energy harvested proportionally (i.e., a direct relation). This voltage can wirelessly transform to power IoT sensor nodes. The pyroelectric method makes use of a special crystalline substance that, in response to temperature changes in its surroundings, produces electrical energy [61].

To collect thermal energy for IoT devices, Vahid et al. [95] proposed a simple design for a nanoantenna. This antenna is said to be the first to harvest nano-thermal energy. The nano-antenna collects infrared radiation (IR) at 30THz. The utilization of IR could have a lot of applications for Internet of Things-based health monitoring systems. The structure of the nanoantenna is shown in the Fig. 9(a). It consists of a glass substrate, ITO (indium tin oxide), and gold that was placed on its base. Alhawari et al. [96] have demonstrated the efficient use of a biochip with a μW size for wearable IoT devices. With a 0.46m^2 surface area, it is a small, lightweight chip. Experimental findings verify 65 - 71 % efficiency, accompanied by a power measurement of about 42μW - 182μW. Fatnani et al. [97] use ambient thermal energy in many IoT applications, such as IR detection and sensing. This concept harvests thermal energy by using the pyroelectric effect in conjunction with IR radiation. They use ceramic PZT buzzers (shown in the Fig. 9(b)), which have pyroelectric properties, and they are utilized to harvest power for areas of 5cm^2 and 20cm^2, in the range of about 0.80 mW to 2.40 mW, respectively. These findings demonstrate the effectiveness of the pyroelectric effect as a thermal harvester.

3.2. *Mechanical energy harvesting*

In IoT applications, mechanical harvesters are probably the most commonly utilized harvesters, with an 80 % high-efficiency rate. They have a wide range of sources, which include vibration, motion (human, plant and machineries), deformation, and pressure. And they can be obtained from various sources, including industrial machinery, bridges, automobiles, buildings, electric appliances, biomotion, etc. Energy in the form of vibration can easily be obtained from various living things, structures, and productions. Another cause of electricity generation is a deformation in the interior molecular structure of a material. The migration of protons and electrons within the material is energized by this deformation, and this leads to the production of electricity [98].

There are various ways to transform mechanical energy into electric energy. The electromagnetic, piezoelectric, and electrostatic transduction methods are a few well-known techniques for scavenging mechanical energy [88,98], as shown in the Fig. 10 [31]. In electrostatic harvesting, two electrodes with positive and negative charges are used. The electricity is produced by the relative motion between two electrodes [99]. Electromagnetic harvesting follows the Faraday law of induction [100]. Current is generated at the coil's end due to the magnet's displacement across the coil. The piezoelectric mechanical harvester uses piezoelectric material [101]. Power is produced when vibrations or motions from an external source compress and deform a piezoelectric material. Detailed mechanisms of these harvesters are given in these papers [102–114].

3.2.1. *Mechanical vibration energy harvesting*

The research in [115–117] examines the techniques for energy harvesting at the micro- and nanoscale utilizing piezoelectric generators, demonstrating the importance of this method for powering IoT devices. Cho et al. [118], in their research, show a RPEH (road-compatible piezoelectric energy harvester). Eight PEHs were placed on a road over a highway rest area. The outcomes demonstrate the capability of harvester to effectively run 24LED indicators to guarantee safety of drivers at night, track traffic data like the number of automobiles/vehicles transferring within the harvesting zone, and continuously monitor the leakage, strain, and temperature inside the harvesters using their sensors. A schematic diagram of the installed RPEH is shown in the Fig. 11(a). Bradai et al. [119] proposed a vibration electromagnetic harvester with a 1.8 V output voltage peak to peak as an energy source in place of batteries for powering a Bluetooth board using a DC voltage of 2 V. Fig. 11(b) shows the diagram of this proposed system. Lu et al. [120] proposed an electrostatic vibrational energy harvester (EVEH) that is based on the electrostatic coupling effect. The device can harvest the power of 1μW at 59 Hz - 148 Hz and 0.5μW at 14 Hz −152 Hz at an acceleration of 2.0 g_{rms}. Using 868 MHz, it was effectively utilized to power the temperature sensor node and transmit data over a distance of up to 10 m

3.3. *Chemical energy harvesting*

Chemical reactions, biochemical processes, and chemical substance transformation are all sources of chemical energy that are easily accessible. An excellent model for the biochemical process is the human body, where food is converted into energy. Similarly, IoT sensor nodes can be powered by chemical energy. Corrosion and biological waste are the most prevalent and accessible chemical energy sources [121].

Chemical energy is mostly converted to electrical energy using microbial fuel cells (MFCs). Biological waste is a resource utilized in MFC to generate electrical energy. The waste is broken down by bacteria producing ions and free electrons through oxidation. Subsequently, the anode picks up the free electrons and transfers them to the cathode. As a result, an electric voltage is produced. MFC schematic diagram is shown in the Fig. 12(a) [122]. MFCs are used to power medium- to large-scale electronic devices in a number of IoT applications [123–125]. Enzymatic biofuel cells find application as a small-scale energy harvesting technology i.e., in biomedical sensor systems [126]. Except for the oxidation process, enzymatic biofuel cells utilize the same harvesting procedure as the MFCs. Proteins are used by enzymatic biofuel cells to initiate the oxidation process. Although these cells are more expensive than MFCs, they have the advantage of being smaller and more efficient [127]. The schematic diagram of the enzymatic biofuel cell is shown in the Fig. 12(b) [128].

The output power of an MFC single unit is extremely low. However, a proper arrangement of MFCs in parallel and series can generate enough voltage and current [129]. Underwater IoT applications can also benefit from MFC. Umaz et al. [130] propose a new idea of Benthic MFCs. Benthic MFCs are important energy-harvesting sources for underwater IoT applications. A Benthic MFC-based harvester utilizes a distributed design with many anodes and cathodes. To ensure proper control over

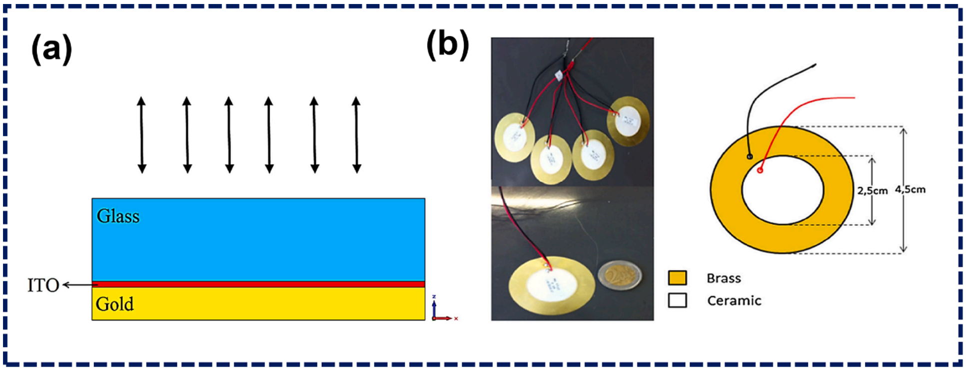

Fig. 9. (a) Nano-antenna structure proposed by Vahid et al. [95]. Copyright 2017, Elsevier (b) Picture of ceramic PZT buzzer [97]. Copyright 2016, Elsevier.

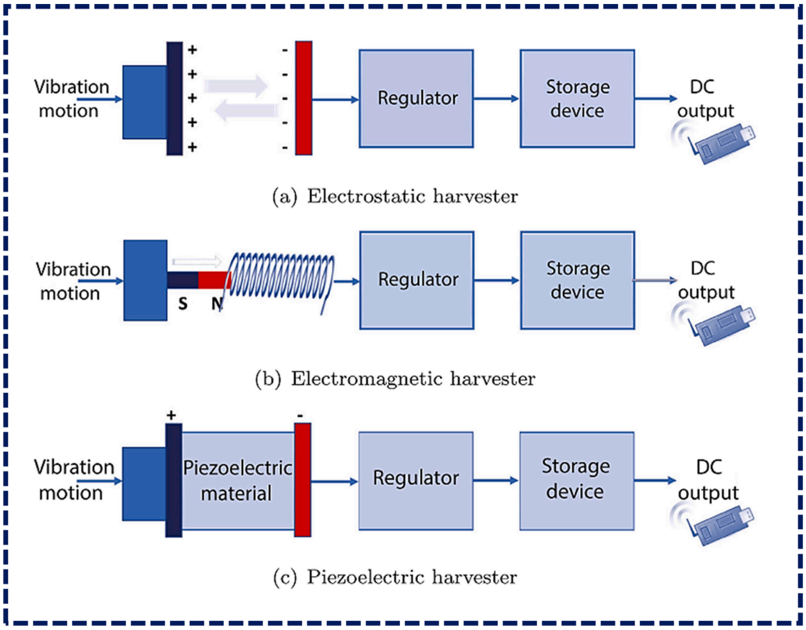

Fig. 10. Mechanical energy harvesters block diagram [31]. Copyright 2020, Elsevier.

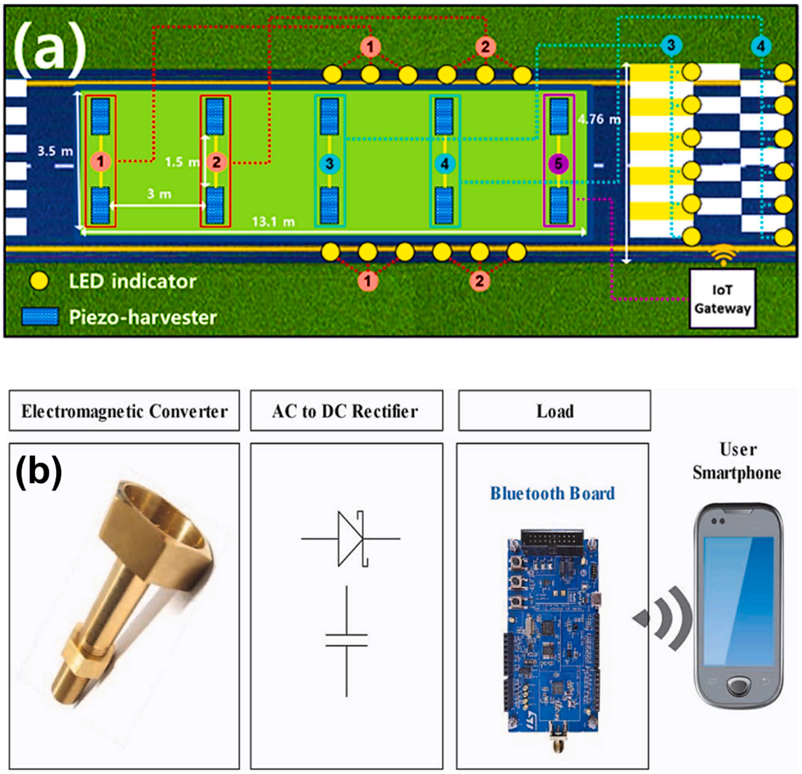

Fig. 11. (a) Schematic diagram of the installed RPEH proposed by Cho et al. [118]. Copyright 2019, Elsevier; (b) Diagram of the proposed system by Bradai et al. [119]. Copyright 2020, IEEE.

the production of power and eliminate system impairments, Benthic MFCs require a power-management system. Ultimately, the experiments demonstrate its effectiveness as a chemical harvester.

3.4. Bioenergy harvesting

Plants are also used as a power source for IoT devices, as this has been shown in various research [131,132]. The plant-as-battery technique aims to make it easier to use wireless sensors for agricultural applications, where some of its popular functions include monitoring plants for detecting pests and measuring ambient humidity and soil moisture.

Konstantopoulos et al. [131] proposed a method that considers plants' capacity to generate electrical signals, which are then harvested through a power management unit. It produces power in the range of 800nW −1400nW each day. It uses a single switch to send the electric

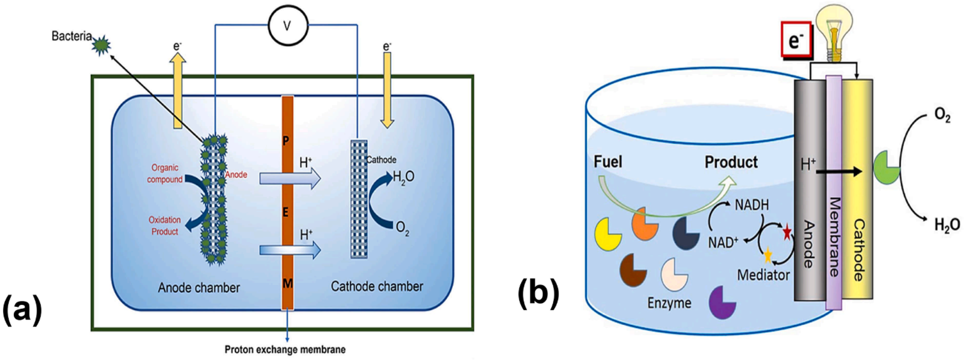

Fig. 12. Schematic diagram of the (a) Microbial fuel cell (MFC) [122]. Copyright 2022, Scientific Research; (b) Enzymatic biofuel cell [128]. Copyright 2015, Royal Society of Chemistry.

potential signal tens of meters out and is based on low-cost and scatter radio principles. Piyare et al. [132], use plants to harvest power. They use them as plant microbial fuel cells (PMFCs). Because of its incredibly low power generation, a PMFC can be used to trigger nodes in IoT networks. This design is particularly useful in areas surrounded by plants, which act as a continuous green power source. These methods can support the advancement of environmentally friendly IoT monitoring applications.

The summary of this whole Section 3 is presented in the Table 2. This Table 2 describes various energy harvesting techniques, the technology that is used to harvest the energy, their power densities, advantages and disadvantages, along with the IoT applications of these harvesters. There are numerous factors that influence the selection of energy harvesting techniques, including the available resource, location, desired performance and IoT application.

4. Cost analysis of energy harvesters

In Section 3, we have explained various energy harvesting techniques that can be utilized to harness energy for powering IoT devices. This section-4 delves into the cost of these harvesters. The cost of designing an energy harvester can change according to the IoT application or service's output power, voltage, and impedance requirements. Energy harvesters are essential for delivering self-sufficient and sustainable power solutions for IoT devices. IoT devices can function without frequent battery replacements by utilizing renewable energy, which lowers maintenance costs and has a smaller environmental impact. The cost of energy harvesters depends upon several factors, i.e., type of energy harvester, material and component, efficiency and power output, size, integration complexity, maintenance, dimensions and form factor, manufacturing process and life span [115,142,143].

The cost factor is one of the most significant issues related to energy harvesters for IoT devices [144]. High efficiency often requires a high cost. In order to address the problem of the cost of energy harvesters for IoT devices, continuing research and development are focused on developing affordable and efficient energy harvesters [145]. This includes developing novel, cost-effective materials and scalable production methods. Additionally, the focus of research is on developing energy harvesters that can be incorporated into existing manufacturing processes and generated in large quantities at a low cost. Another

Table 2
Energy harvesting techniques analysis.

Energy harvesting techniques	Technology Used	Power Density	Advantages	Disadvantages	Applications	Ref.
Solar Energy Harvesting	Photo Voltic Cells	0.006 –15 mW/cm^2	Low manufacturing cost, predictable, high output voltage	Not available at night	Smart monitoring, smart homes and buildings, healthcare, agriculture	[133]
Aeroelastic Energy Harvesting	Piezoelectric	–	Overcomes limitations of conventional methods, effective in a wide range of wind speed	Complex modelling and design, aerodynamic behavior sensitivity	Wearable devices, structural health monitoring, wireless sensors	[134]
Sound Energy Harvesting	Piezoelectric, Triboelectric	1436 μW/cm^2	Pollution free, easily convertible	Limited availability, low power density	Wearable electronics, remote sensing, condition monitoring	[135]
Radio Frequency Energy Harvesting	Antenna, Rectifier Circuits	$1.2 \times 10^{-5} – 15$ mW/cm^2	Readily available, controllable, predictable	Low power density, dependent on distance	Healthcare, smart homes, environmental monitoring	[136]
Wind Energy Harvesting	Piezoelectric	0.065 – 28.5 mW/cm^2	Reduce greenhouse gases, clean and renewable	Intermittent energy source	Remote sensing	[137]
Thermal Energy Harvesting	Thermoelectric, Pyroelectric	147 mW/cm^2, 3.5 μW/cm^3	Utilize heat/waste heat energy, non-polluting	Challenge in material selection, limited temperature gradient	Healthcare, wearable technology, industries	[138]
Mechanical Energy Harvesting	Piezoelectric, Electromagnetic, Electrostatic	4 – 250 μW/cm^3, 300 – 800 μW/cm^3, 50 – 100 μW/cm^3	High output voltage, simple and low cost design, robustness, controllable	Unpredictable, large size, maintenance, noise pollution	Structural health monitoring, wearable devices, industry,	[139]
Chemical Energy Harvesting	Metal Electrodes	–	Sustainable and renewable, reliable	Limited lifetime, limited power density, cost	Wearable technology, underwater IoT applications, smart cities	[140]
Bioenergy Harvesting	Metal Electrodes	–	Utilize organic matter, sustainable and renewable, widely available	Require maintenance, depends on enzymes	Remote monitoring, agricultural applications	[141]

approach to address the cost issue is to optimize the energy management systems of IoT devices to lower their energy consumption. By reducing the power losses, the energy harvesters can work more effectively. Energy harvesting is a significant rapidly developing field that has a lot of potential for economically and sustainably powering IoT devices [146].

In the past few years power management, low-cost, low-power devices, optimization, and autonomous, these words have drawn considerable attention. In regions where battery limitations are a problem, Shafique et al., [147] developed a cost-effective energy harvesting system utilizing a rectenna for powering IoT applications. An energy harvester is created, developed, optimized, and characterized. It merely utilizes RF (radio-frequency) energy of 2.4 GHz from adjacent Wi-Fi/WLAN devices and transforms it into DC power. At the rectenna circuit's output port, the measured power received is −64.4 dBm. Similarly, Barzegar et al., [148] describe the development and testing of an affordable pressure sensor using the MEMS technology for water level monitoring with a range of 0–698 KPa. The sensor is designed to be a part of the IoT to send data via the Internet for monitoring and analysis. The findings demonstrate that, with a full-scale accuracy of 0.31 %, the MEMS sensor offers a reliable and sufficient monitoring system. MEMS technology enables IoT sensors to harvest energy from their surroundings enabling the development of ultra-low-power Internet of Things sensors.

The Table 3 shows the cost analysis of different energy harvesters used for IoT applications. The cost may change depending on factors like quality, efficiency, and specific use.

According to the global market for energy harvesting systems it is expected to grow significantly up to USD 1.53 Billion by 2033, representing a compound annual growth rate (CAGR) of 10.54 % [149]. It shows the steady increase in the demand for energy harvesting systems in the coming years. The survey found that the most significant market segment was light energy harvesting. Transducers hold the largest market share due to their essential function in energy harvesting systems. They transform the various energy resources (i.e., heat, light, mechanical vibrations wind, etc.) into electrical energy. In addition, ongoing advancements in thermoelectric, photovoltaic, and piezoelectric transducers are driving market growth through improving energy conversion efficiency and expanding their range of applications. As a result, transducers are a dominant element in the market for energy harvesting systems due to their vital role in energy conversion, technical advancements, and system miniaturization [149]. Leading companies in the energy harvesting market i.e., ABB Ltd, Analog Devices Inc, Cymbet, Honeywell International Inc, Microchip Technology Inc, Powercast Corporation, etc., are heavily investing in research and development to increase the efficiency and reliability of their solutions. Analog Devices Inc. creates power management solutions to address issues particular to ambient energy harvesting. There devices include LTC3588 designed for vibration-based energy harvesters [150], LTC3108/LTC3109 for thermal energy harvesting [151,152], and LTC3105 for solar energy harvesting [153].

Table 3
Cost analysis of different types of energy harvesters [146].

Energy Harvester	Cost ($)
Solar Energy Harvesting	Initial high cost then low cost
Aeroelastic Energy Harvesting	Not widely commercialized
Sound Energy Harvesting	Not widely commercialized
Radio Frequency Energy Harvesting	Low cost
Wind Energy Harvesting	Low cost
Thermal Energy Harvesting	High cost
Mechanical Energy Harvesting	Low cost but sometimes can be high
Chemical Energy Harvesting	Not widely commercialized
Bioenergy Harvesting	Not widely commercialized

5. Future recommendations and conclusion

IoT is becoming a major part of our everyday lives, making headlines worldwide and creating many new opportunities. But as the number of IoT devices increases, so do the energy requirements. This review presents various energy harvesting techniques for powering IoT devices. However, there are some challenges and limitations with IoT harvesting systems as well. It includes hardware design, software design, energy harvesting modeling, battery storage issues, reliable delivery, size and cost, and environmental impact. Future researchers should focus on the following points mentioned below,

- Future researchers should focus on creating systems for harvesting energy that intelligently handle energy's short-term unavailability. An operating system like this must be able to pick up the task from the point it left off.
- Additionally, researchers should focus on creating intelligent algorithms that can choose energy input sources based on availability, eliminating the requirement for an energy storage component.
- Further researchers should create models of optimal consumption to reduce the energy cost of wireless data transmissions.
- Moreover, they should look into novel techniques for identifying the most suitable method for harvested energy storage, satisfying the following requirements: high energy density, low current leakage, low cycling degradation, and the ability to function in extreme temperatures and other harsh environments.
- Microelectronics has experienced advances in recent years that could be utilized to create reliable, affordable, low-power energy harvesters that are small and compact. With the advancement of nanofabrication technology, it could be possible for IoT devices to become smaller in the future, transforming into the IoNT (Internet of Nano Things). Energy management and harvesting at the nanoscale will be necessary for these IoNTs, opening a significant new area for research in the future.
- The utilization of renewable energy resources reduces environmental pollution. Another issue that needs to be resolved is the use of environmentally friendly materials, i.e., carbon nanowire structure and electroactive polymers, in the design of the electronics of the energy-harvesting system for Internet of Things devices. IoT device developers must consider biodegradable and biocompatible materials for a sustainable future.
- Utilize Artificial Intelligence (AI) techniques i.e., Contract Theory, Reinforcement Learning, and Predictive Analysis to optimize energy allocation, improve efficiency, and enhance IoT device autonomy.
- Utilizing 3D printing additive manufacturing technology will revolutionize energy harvesting by developing cost-effective, multi-source energy harvesters with sustainable materials (minimal material waste) and customized geometries for specific applications. Printed energy devices can be designed with stretchable and flexible materials that can also be used in wearable and biomedical applications.
- Future energy harvesters should combine multiple energy harvesting techniques (multiple sources) to ensure a stable power supply in diverse conditions and maximum power output. These hybrid energy harvesters should include multi-source integration, energy conversion, and storage optimization.
- Blockchain can be used to create decentralized, secure energy trade networks for IoT devices. Enable safe and effective energy transactions between IoT devices by implementing blockchain-based peer-to-peer energy trading, transparent energy networks, and lightweight consensus mechanisms.

We conclude that a considerable amount of energy can be produced for an extended period of time using certain energy harvesting technologies (i.e., PV cells and piezoelectric devices). On the contrary, some other energy harvesting techniques need large circuits to capture the energy and only supply a limited amount of energy at specific times. Still, they do not depend upon the day and night cycle. There are numerous factors that influence the selection of energy harvesting techniques, including available resources, location, desired performance and IoT application.

Energy harvesting is important for extending the lifetime and efficiency of Internet of Things devices. Still, this system also has some limitations that need to be addressed for sustainable growth of IoT devices. This review paper shows the different sources from which the energy can be harvested: solar, sound, wind, aeroelastic, thermal, mechanical, vibration, chemical, and radio frequency, all shown in the flow chart, Fig. 2. These IoT devices have a vast range of applications in healthcare, wearables, infrastructure health monitoring, smart cities, aerospace, environmental monitoring, etc. We must ensure that IoT technology will grow sustainably and become essential to the future world. For its sustainable growth, we need to use eco-friendly materials, eliminate batteries, remove toxic materials, and try to address the recommendations mentioned above. We hope that our review of previous studies and research will focus the attention on future studies that have novel opportunities for resolving some of the challenges we have highlighted for the sustainable growth of IoT devices.

CRediT authorship contribution statement

Ahsan Ali: Writing – original draft, Validation, Resources, Methodology, Formal analysis, Conceptualization. **Hamna Shaukat:** Writing – original draft, Resources, Methodology, Data curation, Conceptualization. **Hassan Elahi:** Writing – review & editing, Visualization, Resources, Investigation. **Shaista Taimur:** Writing – review & editing, Visualization, Validation, Investigation. **Muhammad Qasim Manan:** Writing – review & editing, Software, Resources, Data curation. **Wael A. Altabey:** Writing – review & editing, Visualization, Supervision, Software, Resources, Methodology, Investigation, Conceptualization. **Sallam A. Kouritem:** Writing – review & editing, Visualization, Validation, Resources, Investigation. **Mohammad Noori:** Writing – review & editing, Supervision, Resources, Data curation.

Declaration of competing interest

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

Data availability

No data was used for the research described in the article.

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