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REVIEW

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Wearable Technologies in Energy Harvesting for Sustainable Power Generation in Smart Textiles

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Abstract

Purpose: Wearable textile electronics are vibrant for smart applications across various sectors like health, automotive, sports, industrial work wear, defence, and the military. A key challenge is integrating these smart textiles with external batteries, which are often replaced and recharged frequently due to inadequate power supply. The integration of energy harvesting methods, such as piezoelectric, triboelectric, thermoelectric, and solar systems, provides a sustainable solution. This review examines how energy generation and storage devices can be integrated into self-charging power structures to facilitate long-term energy storage.

Methodology/Design: An Integrated review approach was utilised in this study to identify significant publications for an effective discussion of current material production techniques, innovations, and hybrid methods for harvesting ambient energy in wearable devices. Crucial issues regarding flexibility, energy efficiency, washability, and comfort are thoroughly discussed. Future directions are given for continuous research in this field.

Findings: The study concludes that the successful advancement of wearable energy-harvesting textiles depends on integrating flexible energy-generation, storage, and sensing components into fabrics. It also underscores that interdisciplinary teamwork, textile engineering, and linking material science, nanotechnology, and electronics are essential for achieving comfortable, durable, and scalable smart textiles. This highlights that progress in hybrid energy systems, flexible materials, and textile-compatible fabrication is key to fully recognising self-powered wearable technologies.

Practical and Social Implications: The review underscores innovations in harvesting ambient energy for wearable devices, thereby reducing reliance on batteries and promoting eco-conscious habits. It improves health monitoring with value-added comfort, washability, and durability, making devices more useful, especially for those with chronic illnesses and the elderly. These recent advances could boost employment in smart textiles and green tech, fostering research for more adaptable, inclusive, and energy-efficient wearables that meet modern and environmental needs.

Originality: This study highlights recent advances in research on wearable energy harvesting in smart textiles, encompassing fabrication, hybrid methods, washability, and comfort. This promotes collaboration, user-focused, and innovative wearable technology.

Keywords
Energy harvesting, wearable textile electronics, sustainable power, smart textile.

1 | INTRODUCTION

Electronic textiles have become an integral part of wearable technology due to their lightweight nature, flexibility, electronic functionality, and comfort. In the age of the Internet of Things (IoT), modern wearable electronic devices and their communication systems are tuning into every corner of contemporary society and changing every aspect of human life. There has been a lot of progress in terms of digitalisation and miniaturisation of wearable engineering technology, and its emerging significance to the physical and psychological well-being has had an incredible impact on consumer goods from wearable

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to non-wearable industries (Lin et al., 2022; Liu et al., 2021; J. Pu et al., 2023; Shi et al., 2020; Tao, 2019). In this contemporary generation, textiles are not only known for protecting the body and serving aesthetic purposes, known to be their primary function, but they can also sense, respond, and acclimate to internal and external stimuli to generate and store information and energy (Choudhry et al., 2021; Ghahremani Honarvar & Latifi, 2017). This paradigm shifts from textiles with static functionality to textiles that exhibit dynamic features (Cai et al., 2018; Choudhry et al., 2021; Schneegass & Amft, 2017). Smart wearable electronic textiles have evolved to provide fast, accurate, direct, and convenient information by leveraging human intelligence for cognition and stimulating capacity (Kan & Lam, 2021; Wang et al., 2020). In recent years, smartphones and computers connected to the internet have had a profound impact on human lives. These devices carry a massive amount of information, which interacts with the environment (Rong et al., 2021). They are mostly rigid and user-demanded features, providing limited interactions between the devices and the ambiences, bringing communication nearer to the human body (Heo et al., 2018). It is worth acknowledging that these smart devices appear in a variety of shapes and sizes. It is expected that this new type of electronic device, with its various functionalities and aptness for the human body, would be vital for this field of application. These indispensable needs have led to a rising variety of technologies, most notably, the assimilation of electronic functionality, mechanical aptness, and fully restrained capacity, spawning the concepts of wearable electronics and smart textiles. Generally, wearable electronic textile technology enables the wearer to access information in real-time and has data-input capabilities (Kan & Lam, 2021). It features mechanical flexibility, breathability, knittable integration, and wearable comfort, enabling electronics to become much smaller and more powerful than previously, thereby increasing user movement and comfort (J. Chen et al., 2023; Kan & Lam, 2021; Libertino et al., 2018; Jingjing Zhao et al., 2020).

Wearable devices are systems that are integrated into clothing or wearable products, or directly in contact with the human body, to contribute to health (pulse, skin temperature, blood pressure, respiration rate, sweat content and interstitial fluid, etc) (Rong et al., 2021), detected motion (pressure, strain, etc), to provide vital physiological data (Blood glucose level, Blood Oxygen Saturation, Galvanic skin response, electrocardiography, electromyography, electroencephalography, etc.) for health monitoring purposes (J. Chen et al., 2023; Iqbal et al., 2021; Muhammad Sayem et al., 2020; Sipos et al., 2025; Vidhya et al., 2023). In the field of sports, wearable electronic textiles facilitate physiological monitoring, performance optimisation, injury prevention, motion and biomechanics tracking, rehabilitation support, environmental adaptation, real-time feedback, and coaching (Li et al., 2016; Seçkin et al., 2023; Shen et al., 2024; Yang et al., 2024). Wearables possess robust potential for improving recent medical systems, as they can enhance comprehensive monitoring of various physiological functions and extremely efficient services across numerous fields (Rong et al., 2021). However, the availability of energy poses a significant challenge for wearable devices. These electronic devices typically operate on rechargeable batteries, which limit the devices' overall flexibility and, coupled with their short lifespan, restrict their applications (Ali et al., 2023; Huang et al., 2021). In light of this, wearable electronic devices require suitable energy sources, as their operation depends on an uninterrupted, steady, and adequate power supply. Moreover, different forms and applications of wearables require different amounts of energy to work (Rong et al., 2021; Zhang et al., 2021). It is important to design and choose reliable energy supply schemes with appropriate structures, sizes and energy concentrations for wearable electronics (Ali et al., 2023). The cost of batteries to power wearables is associated with risks such as leakage of toxic substances (bismuth telluride), fire and explosion hazards, limited device lifetime, and frequent replacement (Avari et al., 2024; Rong et al., 2021; L. Wang et al., 2023). Rong et al. (2021) assert that an alternative energy solution for wearable electronics involves harvesting energy from the human body and the ambient environment, thereby reducing dependence on conventional batteries and enabling continuous, sustainable device operation. Several technologies can be used to harvest energy, including thermoelectric generators (TEGs), photovoltaic (PV) cells, triboelectric nanogenerators (TENGs), piezoelectric nanogenerators (PENGs), biofuel cells (BFCs), electromagnetic generators (EMGs), and radio frequency (RF) harvesters (Khan & Khan, 2022; Shuvo et al., 2022; Yu et al., 2024). These innovative technologies could be used in either single or hybrid layouts (Jinwei Zhao et al., 2020). The aforementioned procedures need to be well-designed in terms of structure, size, power density, and energy output, centred on the application of importance (Rong et al., 2021).

The power generators, however, need to be well-adapted to the human body and be stable, durable, non-toxic, and flexible enough. Energy harvesting technologies offer an alternative to conventional batteries for powering wearable electronic textiles, thereby enabling continuous, maintenance-free operation (Dolez, 2021; Köhler et al., 2011). Approaches such as photovoltaic cells, thermoelectric generators, piezoelectric and triboelectric nanogenerators, biofuel cells, electromagnetic generators, and

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RF harvesters provide exceptional benefits depending on the application requirements (Heo et al., 2018). However, numerous experiments are still needed to enhance power density, flexibility, biocompatibility, and seamless assimilation into textiles without compromising comfort (Li et al., 2024; Sun et al., 2024; Yang et al., 2020b). This review aims to provide an overview of energy harvesting technologies, their fabrication techniques, the materials used, and the integration with energy storage systems, illustrated in Figure 1. It also examines performance dynamics in energy-harvesting devices, the application of energy-harvesting smart textiles, challenges and research gaps, and future directions and innovations. Wearable textile electronics provide physical flexibility and adaptability. They are designed to be seamlessly integrated into everyday garments, enabling health-monitoring functions and personal expression (Azani & Hassanpour, 2024; Stoppa & Chiolerio, 2014). The need for this review is to address the challenges of embedding energy-harvesting techniques into electronic textiles. Previous research focuses on fabricating conductive materials, improving functionality, and the acceptance of wearable devices in daily life. The review further underscores the potential of energy-harvesting textiles for wearables across various industries, including the military, healthcare, sports, and fashion, and emphasises the need to address these challenges to realise their full potential. While previous studies address issues of energy availability, stability performance, integration of wearable electronics, and practical applications, this review distinguishes itself by incorporating condition-normalised performance comparisons, practitioner-oriented design, environmental conditions, and textile-level implementation.

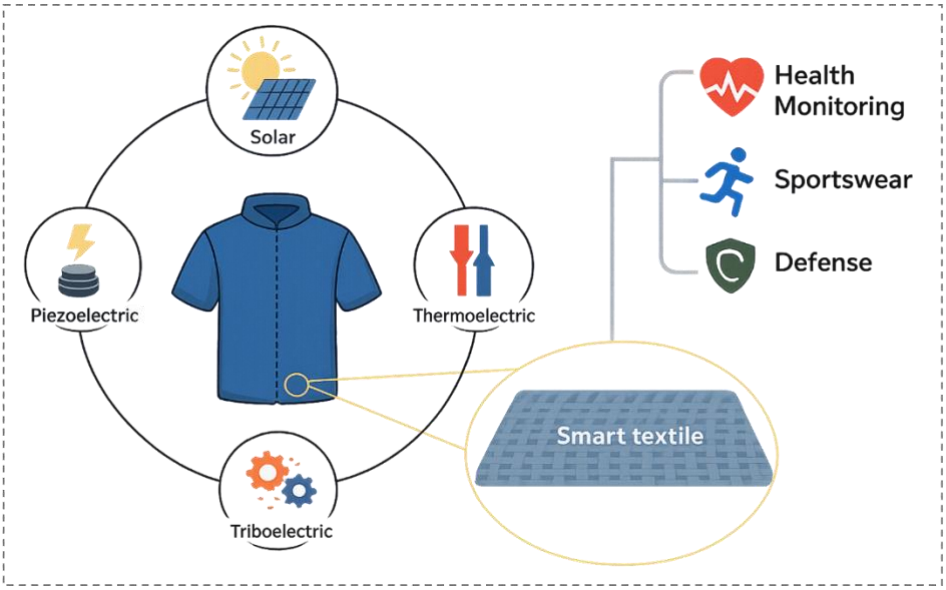


Figure 1. Illustration of wearable technologies for sustainable energy harvesting in smart textiles.

2 | METHODOLOGY

The study adopted the integrated review approach (IRA), which allows the combination, comparison, and synthesis of findings using different methodologies (qualitative and quantitative studies, as well as theoretical and empirical works). The approach also provided a comprehensive understanding of the topic and is particularly well-suited to combining heterogeneous research designs to inform both theory and practice (Whittemore & Knafl, 2005). The study employed a systematic search strategy in the Scopus database using the specified search terms. The Scopus online academic database was primarily used to search and extract data for the study. Although other online databases, such as the Institute of Electrical and Electronics Engineers (IEEE), PubMed, ERIC, JSTOR, DOAJ, Web of Science, provide valuable resources, they are often more specialised, which can sometimes make comparison extremely difficult; In contrast, Scopus offers broader coverage, which facilitates easier analysis and comparison (Fobiri et al., 2024; Gusenbauer, 2022). This distinction makes Scopus a preferred online database choice for the study. The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) framework was used to enhance the report of the database, reduce bias, evaluate the selection process, and check for methodological quality. The chart illustrated in Figure 2 maps out the number of records identified through database search (n =314), records screened (n = 314), full-text studies assessed for eligibility (n = 195), eligible studies (n = 185), records excluded (n = 139), studies excluded without full-text (n =56), additional ineligible studies excluded (n = 23) and the included studies (n =162). This chart

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provides a clear and concise visual representation of the study selection process in systematic reviews and meta-analyses.

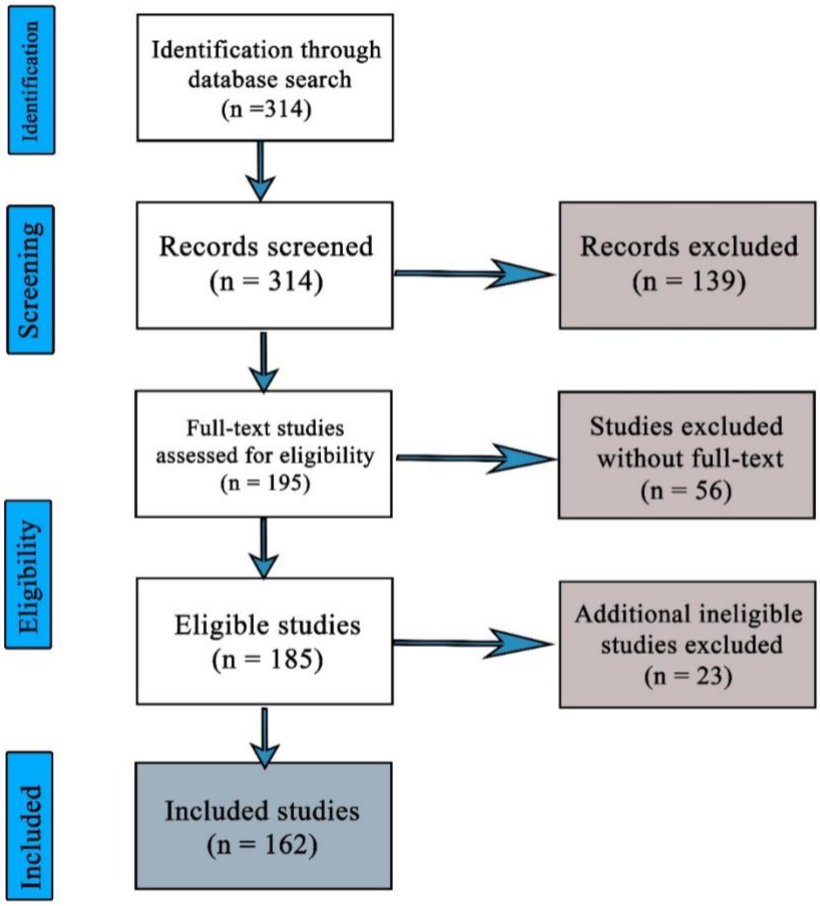


Figure 2. The Graphical Presentation of the PRISMA flowchart used for study selection.

2.1| Publication Trend and Contributing Regions Based on Title, Abstract, and Keywords

The research trend reflects advances in scientific studies, charts, and industrial procedures, aligning with the growing interest in wearable textile electronics for sustainable power generation and innovative applications in smart wearables. The trace in recent progress and research trend regarding wearable technologies, a search was conducted in the Scopus online database with the keywords ("wearable technology" OR "wearable devices" OR "wearable electronics") AND ("energy harvesting" OR "self-powered" OR "power harvesting") AND ("smart textiles" OR "e-textiles" OR "electronic textiles" OR "intelligent fabrics"). The search was conducted on 1st September 2025 and yielded 314 documents from the online database. To understand the current state of the field of wearable technologies, the document obtained was analysed without exclusions, covering the period from 2003 to 2025. With the 314 papers obtained from the database, 190 (60.5%) comprise articles, 78 (24.8%) represent reviews, 26 (8.3%) are conference papers, 13 (4.1%) are book chapters, 6 (1.9%) are books, and 1 note represents 0.3%. The data was analysed by year of publication to determine the series and progress. It was observed that, in 2003, one document was published; in 2004, 0; in 2005-2007, 0; and in 2008, 1. No documents were recorded from 2009 to 2011. The past few years have seen both decline and progress in the field of wearable technologies. The concept began to gain attention and popularity in 2019, when 9 documents were recorded. In 2020, 34 papers were recorded, 30 in 2021, 35 in 2022, 46 in 2023, 61 in 2024, and 56 as of September 2025. The contributing countries were analysed to identify the top 10 countries contributing to the development of wearable textile electronics to enhance their applications in the military, sports, and health sectors (Choudhary & Ramratan, 2020; Guru et al., 2025). The statistics illustrate that China is leading as the most contributing country with 151 documents published, with the United States being in the second position with a total publication of 63, followed by the United Kingdom, which has a total of 37 documents published. The fourth contributing country on the list is India and South Korea, with a total publication of 25, followed by Singapore, which has recorded 19 documents, Hong Kong, which has recorded 16, Germany, which has recorded 14, and Canada and Portugal, recording

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a total of 10 documents respectively. Figure 3a and Figure 3b are illustrations of the best 10 contributing nations and the publication trend in the field of wearable textile electronics.

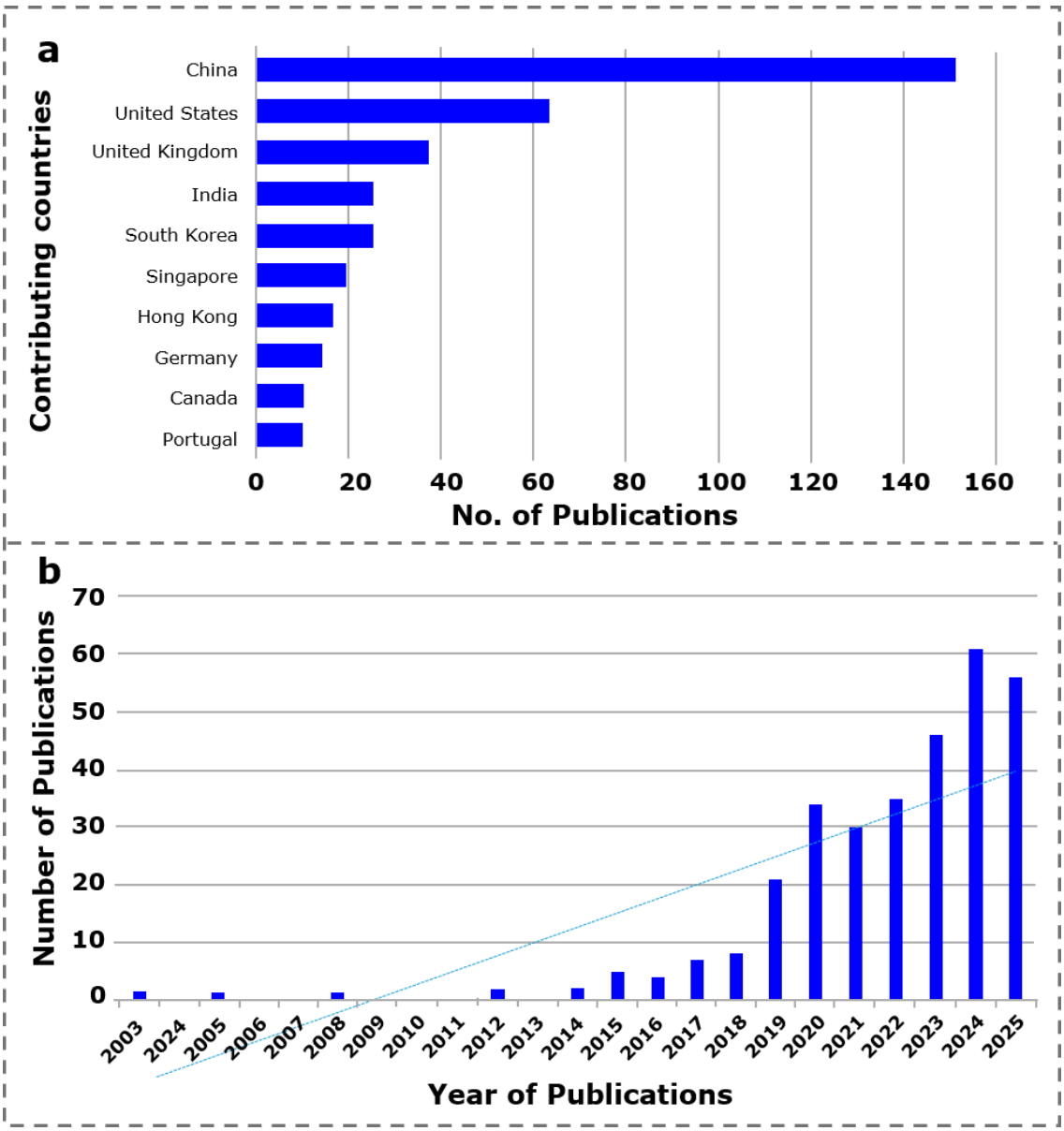


Figure 3. (a) Contributing Countries and (b) publication trends on wearable textile electronics for energy harvesting.

2.2| Analysis of Keywords

A co-occurrence analysis of keywords from the included studies was conducted using VOSviewer (version 1.6.20) to examine the frequency of keyword co-occurrence in published studies. The document extracted provided (n=314), the minimum occurrence threshold for a keyword was set at 5, resulting in 183 keywords meeting the benchmark. The scrutiny generated 7 clusters, with a total of 6,001 links and a total link strength of 15,695. The keywords that emerged were "Smart Textile", "Wearable Technology", and "Nanogenerator". Smart Textiles occurred 227 times with 182 links and a total link strength of 2,141. Wearable technology appeared 150 times, with 180 links and a total link strength of 1,452. Correspondingly, Nanogenerator was a significant keyword in cluster 3, occurring 97 times with 161 links and a total link strength of 1,022. Figure 4 illustrates the results of the keyword co-occurrence analysis, showing the frequency, clustering, and interconnections among the extracted keywords. Table 1 also presents the top ten (10) keyword co-occurrences from the keyword analysis conducted with VOSviewer. The most frequently occurring keywords were smart textiles, wearable technology, nanogenerator, triboelectricity, triboelectric nanogenerator, energy, wearable sensors, weaving, textiles, and yarn.

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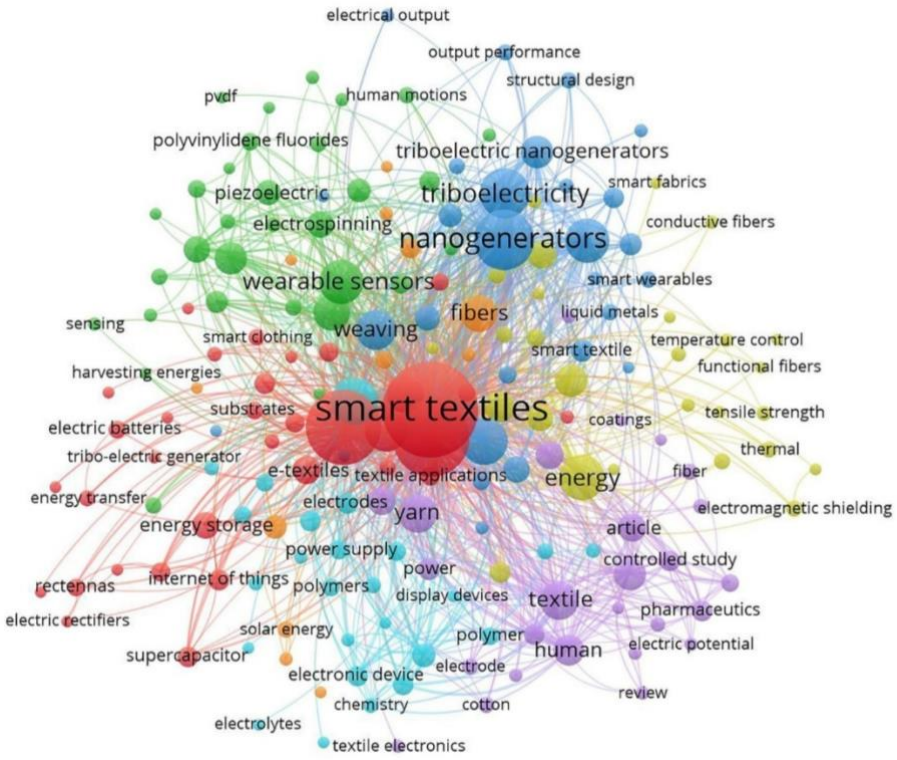


Figure 4. Co-occurrence of keywords.

Table 1: The top ten co-occurrences of keywords

Keywords	Number of occurrences
1. Smart Textiles	227
2. Wearable Technology	150
3. Nanogenerator	97
4. Triboelectricity	68
5. Triboelectric Nanogenerator	54
6. Energy	57
7. Wearable Sensors	53
8. Weaving	45
9. Textile	42
10. Yarn	41

3 | OVERVIEW OF ENERGY HARVESTING TECHNOLOGIES

Wearable devices used by humans have demonstrated substantial development in convenience. These technologies comprise smart clothes, smart glasses, and biometric sensors. Their operation requires power ranging from several milliwatts to numerous tens of watts to function (Choi et al., 2017). These devices consume a high quantity of power, resulting in augmented battery weight and requiring frequent charging and replacement (Manghwar et al., 2024). In the military, for instance, soldiers carry a 7-8kg battery to power GPS devices, telecommunications equipment, and other paraphernalia for 72 hours (Choi et al., 2017; Yuan et al., 2017). However, over the years, heated clothing has been used to warm the body during open-air activities at cold temperatures, requiring ~10 W and an estimated 1kg of lithium-ion battery, which charges every 3-4 hours (Rolo et al., 2023). As research progresses, scholars have noticed that such demands cannot be fulfilled by batteries alone. Therefore, energy harvesting devices have been studied and examined to provide an additional energy source for batteries, and potentially independent energy sources for the permanent use of wearable devices without the restrictions associated with power distribution and consumption (Liang et al., 2025). Human energy can originate from physical and chemical sources, and it comprises kinetic and thermal energy from the human body (Ferreira et al., 2025). Wearable thermoelectric devices (Kim et al., 2014) convert heat from the body into electricity of numerous μW simultaneously without affecting the human body. The body, however, generates kinetic energy in various forms by using muscles, such as motions of the joints, foot strike, knee, hip, arm, elbow, ankle, and motion of the upper body (Choi et al., 2017; Tang et al., 2025; Yang et al., 2023).

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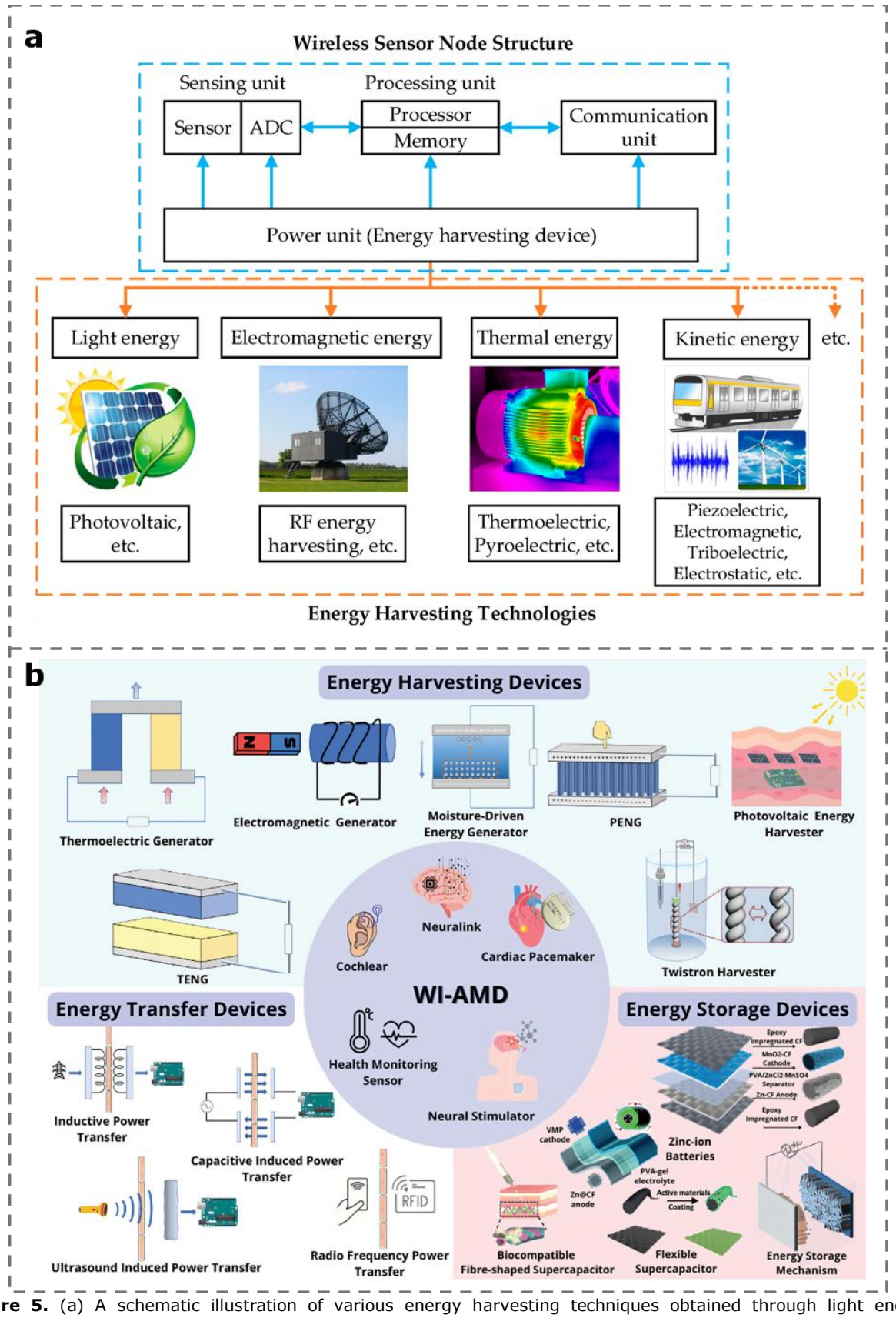


Figure 5. (a) A schematic illustration of various energy harvesting techniques obtained through light energy (photovoltaic), electromagnetic energy (RF energy), thermal energy (thermoelectric and pyroelectric energy), and kinetic energy (piezoelectric, electromagnetic, triboelectric, and electrostatic). The diagram also depicts the wireless sensor node structure and power unit (energy harvesting devices) with sensing unit, powering unit and communication unit (Tang et al., 2018) (This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license). (b) a schematic presentation of energy harvesting and transfer solutions (thermoelectric generator, electromagnetic generator, moisture-driven energy generator, piezoelectric, photovoltaic, triboelectric, and twistron energy harvester) with energy transfer devices (inductive power transfer, capacitive induced power transfer, ultrasound induced power transfer, and radio frequency power transfer) with energy storage devices (zinc-ion batteries, flexible supercapacitor, biocompatible fibre-shaped supercapacitor, and other energy storage mechanism). The WI-AMD is a networking technology that allows high-speed data transfer over short distances (neuralink, cardiac pacemaker, cochlear), which are common in health monitoring sensors (Gao et al., 2024) (This is an open-access article distributed under the terms of the Creative Commons CC BY license)

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Figure 5 is an illustration of various energies from natural and artificial sources (electromagnetic radiation, heat, sunlight, vibration, motion and magnetic energy) (Tang et al., 2018). These springs of energy can be harvested using several techniques, such as piezoelectric, thermoelectric, photovoltaic, triboelectric, radio frequency, pyroelectric, electrostatic, and electromagnetic. These techniques for energy harvesting are particularly suitable for smaller devices, such as portable electronics and wearable devices (Hadas et al., 2018; Ibrahim et al., 2017; Prauzek et al., 2018; Tang et al., 2018; Wei & Jing, 2017). The primary goal of energy harvesting is to convert energy from one source to another that can be used to power electronic devices (Prauzek et al., 2018). Energy harvesting sources can be categorised into external and ambient sources (Shaikh & Zeadally, 2016). External sources emit energy into the environment, with the intention of being harvested by nodes, whereas ambient sources are accessible within an environment without requiring any external supply (Jiao et al., 2017). However, these techniques can directly extract ambient energy when implemented in environmental monitoring nodes under surveillance and use it to power the nodes of the EWSN to prove their performance and probably extend their lifespan (Prauzek et al., 2018; Zhou et al., 2014). Table 2 presents energy harvesting modalities with their specific devices, power densities, operating conditions, and comparability notes. The reported power densities are highly dependent on operating conditions such as illumination intensity, mechanical loading, motion frequency, and temperature gradient. The values across different energy harvesting modalities should not be construed as directly similar unless regulated under identical conditions. Table 2 differentiates wearable-realistic standards from laboratory-optimised demonstrations to ensure a credible and transparent evaluation.

Table 2. Comparison of Power Outputs from Wearable Energy Harvesting Technologies with Operating Conditions

Energy Harvesting Modality	Specific Device / Architecture	Power Density (Normalised)	Operating Conditions	Comparability Note	Reference
Photovoltaic (PV)	Flexible indoor photovoltaic cell	~10–100 μW/cm²	Indoor illumination: 200–1,000 lux (LED/fluorescent lighting)	Comparable only among indoor photovoltaic systems	(Kim et al., 2022; Xiong & Lee, 2019)
	Flexible outdoor photovoltaic cell	Up to ~100 mW/cm²	Direct solar irradiation: ~1 sun (AM 1.5, ≈1000 W/m²)	Not comparable with indoor PV or non-solar harvesters	(Kim et al., 2022)
Thermoelectric Generator (TEG)	Conventional wearable thermoelectric generator	~10 μW/cm²	Skin–ambient temperature gradient (ΔT ≈ 3–5 °C)	Comparable among body-heat-driven wearable TEGs	(Kim et al., 2022)
	Optimised wearable TEG	~35 μW/cm²	Enhanced thermal interface; ΔT ≈ 5–7 °C	Comparable within optimised wearable thermoelectric systems	(Nozariasbmarz et al., 2020)
	High-performance TEG module	454.9 μW/cm²	Laboratory gradient ΔT = 10 °C	Higher than typical wearable conditions; limited real-world comparability	(Yuan & Zhu, 2020)
	TEG with phase-change-material (PCM) heat sink	~2.9 mW/cm²	Controlled thermal management; stabilised ΔT under laboratory conditions	Not representative of realistic wearable scenarios	(Yuan & Zhu, 2020)
Triboelectric Nanogenerator (TENG)	Fabric-based triboelectric nanogenerator	~1.48 mW/cm²	Periodic contact–separation motion; mechanical excitation frequency ≈ 2–5 Hz	Motion-dependent benchmark under controlled testing	(Paosangthong et al., 2019)
	Electrospun nanofiber TENG (NF-TENG)	~0.13 mW/cm²	Low-frequency deformation (≈1–3 Hz bending/stretching)	Comparable within textile-based TENG structures	(Tao et al., 2025)
	Woven textile TENG	~0.00065 μW/cm²	Irregular human body motion (walking/arm swing)	Realistic wearable output but very low power density	(Dong et al., 2017; Shaikh & Zeadally, 2016)

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Motion-Based (Piezoelectric / Electromagnetic)	Piezoelectric wearable motion harvester	~4 μW/cm²	Human motion: walking/limb movement; frequency ≈ 1–3 Hz; force <10 N	Highly dependent on user motion intensity and device placement	(Kim et al., 2022)
Radio-Frequency (RF) Energy Harvesting	Ambient RF energy harvester	~1 μW/cm²	RF sources (Wi-Fi/GSM); field strength ≈ 0.1–1 V/m; distance ≈ 5–20 m from transmitter	Not directly comparable with mechanical or thermal harvesters	(Kim et al., 2022)

3.1| Thermoelectric Energy Harvesting

Thermoelectric energy harvesting is a technique that exploits the Seebeck effect, where a temperature difference traversing a thermoelectric material produces a voltage, facilitating the direct conversion of heat into electrical energy without the need for moving parts (Sanad et al., 2020). In wearable textile electronics, thermoelectric generators (TEGs) are embedded into garments to capture body heat and convert it into electricity, making them ideal for powering low-energy devices such as GPS trackers, communication modules, and health monitors (Yang et al., 2023; Zhu et al., 2022). However, the human body naturally produces heat up to 100 W (watts) at rest, with a skin surface temperature around 32–35 °C. When the body is in contact with a cooler environment, a temperature gradient forms between the skin and the surroundings (Yang et al., 2023). TEGs apply this lower temperature difference, typically 3–10 °C, in wearable applications to produce electrical output (Nozariasbmarz et al., 2020; Xing et al., 2023). The generated power, however, has a density that usually ranges from ~10 μW/cm² in regular devices to 35 μW/cm² (microwatts per square centimetre) in advanced structures, and can reach mW-scale outputs when optimised with thermal management resolutions such as phase change materials (PCMs) (Lee et al., 2017; Xin et al., 2024; Zhu et al., 2022). Wearable TEGs are fabricated from bismuth telluride (Bi_2Te_3) or flexible organic/inorganic composite materials to achieve flexibility, efficiency, and wearability. Without compromising comfort, recent innovations in stretchable TEGs have enabled a seamless integration of fabrics (Han et al., 2024; Sattar & Yeo, 2022).

There are challenges in minimising their performance in low-temperature-gradient environments, but improving mechanical durability under repeated bending and reducing material cost during production are essential (Fan et al., 2023). In terms of sustainable power generation, thermoelectric energy harvesting offers a continuous, passive energy supply as long as there is a difference in temperature, rendering it a promising alternative to batteries in wearable electronic systems. TEGs are highly dependent on external temperatures and can function day and night, outdoors and indoors, with dependency on environmental conditions (Rong et al., 2021; Yu et al., 2024; Zhu et al., 2022). This makes TEGs valuable for critical applications such as military communications, remote field operations and health monitoring (Dargusch et al., 2020; Jia et al., 2021). Regardless of the prevalent use of high thermoelectric efficiency near room temperature, bismuth telluride (Bi_2 Te_3) raises concerns for wearable applications due to the potential toxicity of tellurium-based compounds (Wong et al., 2025). Persistent skin contact, mechanical wear, and material degradation may raise biocompatibility and environmental safety issues, which may limit its suitability for elongated use in body-worn textiles. Consequently, the attention of researchers has shifted towards finding alternative materials (polymer-inorganic composites, organic thermoelectrics, carbon-based systems) to provide improved flexibility, reduced toxicity, and enhanced safety and comfort when using wearable textile electronic systems (Jamil & Holden, 2025).

3.2| Piezoelectric Energy Harvesting

Piezoelectric energy harvesting is a technology that transforms energy from vibration pressure, or motion, into electrical energy by means of piezoelectric resources. Piezoelectric energy can be harvested through various means, such as vibrations, movements, and motions of objects in our surroundings, which can be conveniently converted into electrical energy by piezoelectric generators (Hossain et al., 2022). This form of energy has been demonstrated to be promising in the field of wearable technology (Hossain et al., 2022; Tian et al., 2018). However, various studies reveal that most of the energy associated with human mechanical energy due to body motion, such as running, walking, hiking, talking, and breathing, is wasted, which can all be converted into electrical energy in wearable textiles (Jung et al., 2015). Meanwhile, researchers reveal that piezoelectric energy sources utilise human motion to self-

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power wearables. Piezoelectricity materials such as Polyvinylidene fluoride (PVDF), nylon-11, Lead Zirconate Titanate (PZT), Polyurethane (PU) composites, lithiul tantalate ($LiTaO_3$), langasite ($La_3Ga_5SiO_{14}$), sodium tungstate (Na_2WO_3), Barium Titanate ($BaTiO_3$), Zinc Oxide (ZnO) nanowires, PZT polymer composites, PVDF+ZnO nanofibres Composites, and $BaTiO_3$/elastomer composites gallium orthophosphate ($GaPO_4$), potassium niobate ($KNbO_3$), (Bhadwal et al., 2023; He et al., 2025; Kim et al., 2018; Sabry & Hussein, 2019; Wan et al., 2023) are ideal for power generation in smart wearables due to their exceptional properties and ability to pressed and compressed simultaneously to create electric charges that accumulates in the material (Hossain et al., 2022; Liu et al., 2013). When retreated, an outer electrical supplier either compresses the piezoelectric substrate, and these features make it extraordinary for wearable textiles.

3.3| Solar (Photovoltaic) Energy Harvesting

Solar (Photovoltaic) is one of the alternative energy sources that make up an increasing amount of electrical demand in many countries over the past few decades (Mather & Wilson, 2017). Photovoltaic (PV) is an energy harvesting technique that converts sunlight into electricity using PV cells (Mather & Wilson, 2017; Satharasinghe et al., 2020). Wearable textiles require flexible PV cells that can be integrated into fabrics or garment surfaces to generate sustainable power (Ali et al., 2024; Czarnecki et al., 2024; Satharasinghe et al., 2020). PV harvesters offer a renewable and eco-friendly energy source with higher power density, making them appropriate for powering health monitoring devices, communication devices, and sensors (Ali et al., 2024; Ilén et al., 2024). However, advances in organic photovoltaic (OPV) cells, perovskite solar cells, and dye-sensitised solar cells (DSSCs) have enabled the development of semi-transparent, thin-film, and flexible components that can be implanted into textiles without compromising aesthetics and cosiness (Bandara et al., 2022; Ke et al., 2023; Yang et al., 2014; Yun et al., 2014). Despite this, challenges and limitations persist in utilising PV cells in wearables, which include a dependency on sunlight availability, restricting continuous power generation indoors or in low-light conditions. Solar energy harvesting remains one of the most promising techniques for replacing batteries in wearable systems due to its scalability and embedding capacities.

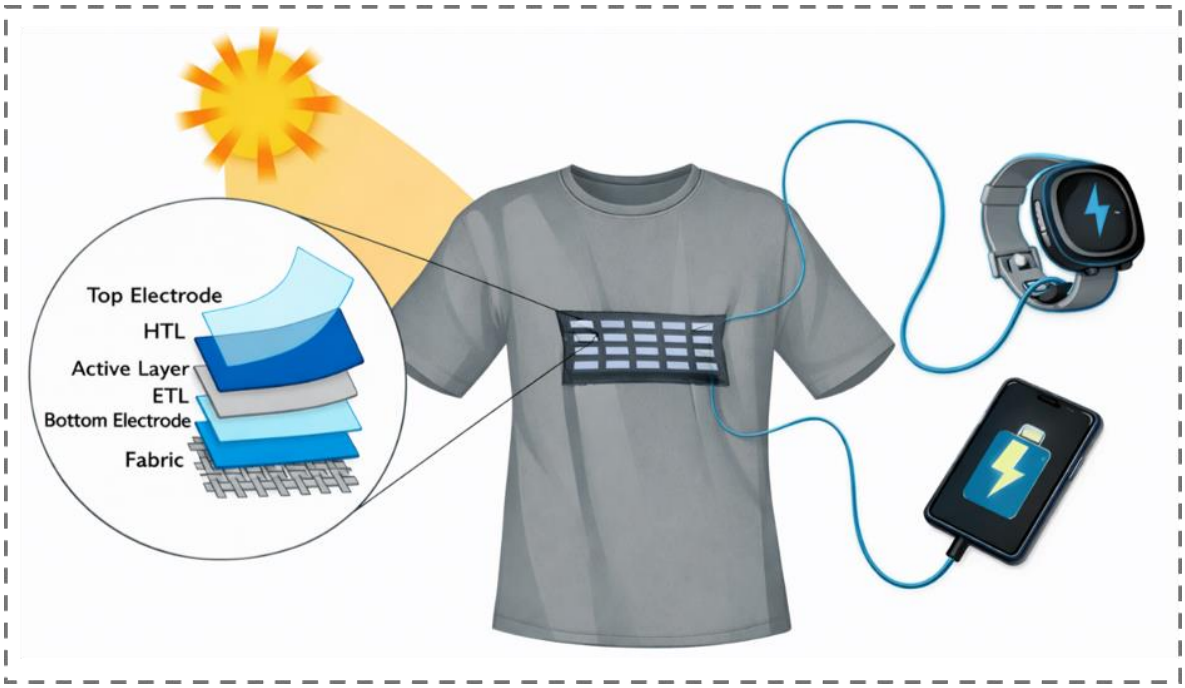


Figure 6. Textile solar cells that can power wearable and portable devices (Ali et al., 2024) (This publication is licensed under CC-BY 4.0)

3.4| Triboelectric Nanogenerators (TENGs)

Wang and co-workers first developed triboelectric nanogenerators (TENGs) for transforming arbitrarily disseminated, asymmetrical, and wasted low-frequency energy into electric power (Fan, Tian, & Lin Wang, 2012; Fan, Tian, & Wang, 2012; Huang et al., 2021; Wang, 2020). TENGs are innovative energy-harvesting devices that generate electricity from mechanical energy through the combined effects of triboelectricity (contact-induced charge transfer) and electrostatic induction. TENGs, however, can

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generate energy using the coupling effect (when two materials with varying electron affinities come into contact and then separate, electrons are transferred, creating a potential difference that can be used as electrical energy) (Cui et al., 2022; Huang et al., 2021; Kim et al., 2021). It is popularly known for its low-cost, diverse choice of materials, easy fabrication, and broad range of applications. TENGs are attractive in wearable textile applications because they can detect human motion (stretching, bending, walking, and subtle body movement) into power (Shin et al., 2023; Yang et al., 2020b; Zhao & Hu, 2024). TENGs can be embedded in fabrics using nanostructured surfaces, flexible polymers, and fibre-based architectures to conserve stretchability, breathability, and comfort of the garment. In terms of performance, TENGs can reach a maximum output of several mW/cm² up to (>10–100 V), rendering them independent of frequency so that most of the generated power can effectively be used to power devices (Zi et al., 2016), making them ideal for powering low-energy devices such as health monitors, communication systems, and sensors (Bairagi et al., 2022; Gao et al., 2024; Neelakandan et al., 2024; Peng et al., 2023). Moreover, TENG's ability to harvest energy from irregular, low-frequency body motions gives it a strong advantage in wearable electronics over conventional energy harvesting techniques (X. Pu et al., 2023; Zi et al., 2016). Challenges remain in improving and maintaining high efficiency in humid environments, developing cost-effective, scalable production techniques, and durability under repeated mechanical stress (Gunawardhana et al., 2022; J. Zhang et al., 2024; Zhao & Shi, 2023). Unceasing research on advanced materials, hybrid integration, and surface engineering with energy sources is providing a significant aid to overcome some limitations.

3.5| Comparison of Energy Harvesting Mechanisms (efficiency, output, limitations)

The various energy-harvesting techniques offer unique advantages and pose distinct challenges when embedded in wearable textile electronics. PENGs and TENGs energy harvesters typically have a high voltage, and current manufacturing techniques have considerable potential for further reducing the size of these devices (Ali et al., 2023). However, their output is reliant on motion moderation and suffers from performance deprivation in humid environments (Repoulias et al., 2023; J. Zhang et al., 2024). PV cells provide comparatively high power density under sunlight, with efficiencies reaching 15-25%; hence, their performance is limited indoors or in low-light conditions (Lazaroiu et al., 2023). TEGs generate continuous, passive power by converting body heat into electricity, but their efficiency is generally low (4-7%) due to small temperature gradients between the skin and the environment. Consequently, EMGs offer instantaneous and extraordinary power during large body motions, but are dense and less applicable for embedding into flexible (Zhou et al., 2023). On the other hand, RF harvesters can convert energy from ambient wireless indicators, but generally offer low power levels (μW range), which limits their function to ultra-low-power electronics (Borges et al., 2015). Researchers across various fields have identified several challenges in integrating energy-harvesting technology into wearables, including limited energy production, reduced energy output, excess power requirements, and material compatibility. On the contrary, hybrid systems can syndicate multiple mechanisms (TEG, TENG, PV, and BFC) and can be reconnoitred to improve energy availability, stability, and efficiency for practical applications. Figure 7 illustrates the variations of energy harvesting mechanisms (piezoelectric, triboelectric, magnetoelastic, thermoelectric, electromagnetic, antenna-coils, hydrovoltaic, catalytic, and photovoltaic).

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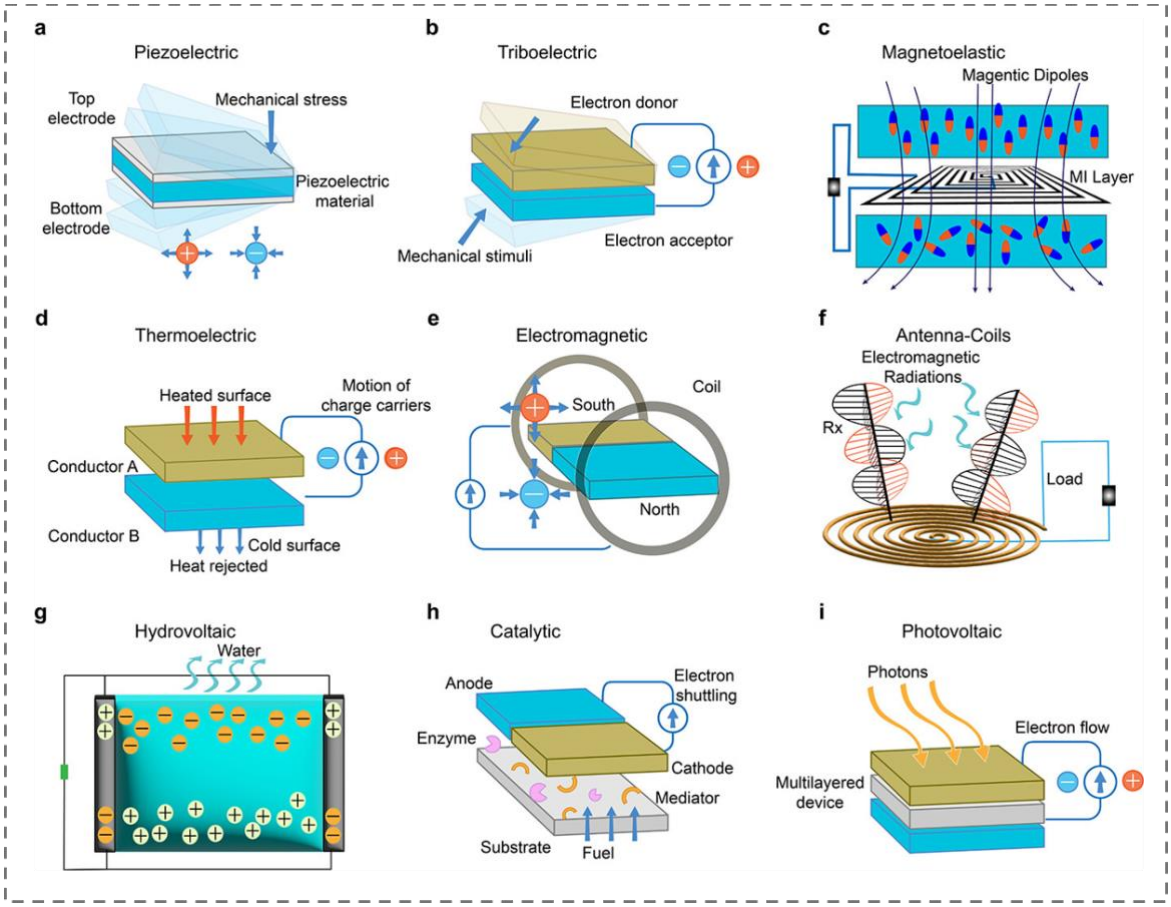


Figure 7. Schematics of different energy harvesters' working mechanisms. (a) Piezoelectric, (b) triboelectric, (c) magnetoelastic, (d) thermoelectric, (e) electromagnetic, (f) antenna-coils, (g) hydrovoltaic, (h) catalytic, and (i) photovoltaic (Ali et al., 2024) (This publication is licensed under CC-BY 4.0).

4 | MATERIALS AND FABRICATION TECHNIQUES

Embedding energy harvesting into smart textiles necessitates the use of advanced materials and flexible fabrication techniques that enhance durability, wearer comfort, and electrical performance (Dolez, 2021). The selection of these materials and the fabrication technique is critical in achieving sustainable power generation without compromising the properties of the textile material. Recently, there has been a slight progress in reducing the capabilities of sophisticated computational electronic devices, marked by truncated-power communication technologies. This involves an inclination towards powering devices with extended life cycles, extraordinary energy efficiency, and fast and inexpensive fabrication techniques, utilising lightweight power sources. Integrating TEGs, TENGs, PV, BFC, and PEH materials and innovative production techniques with conservative textile processes has established the development of the wearable technology field, which can fulfil this resolution. Amongst the variety of materials demonstrating TEGs, TENGs, PV, BFC, and PEH, conductive polymers are further considered due to their numerous exceptional characteristics required in flexible energy generation. It has been recommended that fibre-based electronic devices have the best features for human garments, such as permeability, lightweight, flexibility, stretchability, and ideal interface platform options between the electronic devices, human body and the environment (Mokhtari et al., 2020). The conductivity of fibres and yarns has been exploited, not only for conducting electricity and in sensing, but also in delivering anti-static, antimicrobial, and electromagnetic shielding (EMS) properties (Qu & Skorobogatiy, 2015; Raji et al., 2017; Xue et al., 2012). There has been a lot of progress by researchers and industry practitioners. A study by Raji et al. (2017) reveals that researchers and industry have produced conductive yarns out of whole metals (metallic yarns, hybrid yarns) out of a combination of metallic yarns and conventional textile yarns, and laminated yarns with conductive films, coated with conductive solutions.

In contrast, nanomaterials and nanostructures have improved the performance of energy-harvesting devices due to a surge in the strength of the physical effects of energy-harvesting technologies (Dragoman, 2023). At this scale, interfaces and exteriors perform a cumulative role in light phonon sprinkling, while quantum effects such as tunnelling and ballistic charge carrier transport mostly inspire new designs for energy harvesting and demand nanomaterials and nanostructures with precisely

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controlled properties (Dragoman, 2023; Dragoman et al., 2024; Peri et al., 2022; Yang et al., 2025). The integration of nanomaterials and nanostructures into energy harvesting functions through synergistic mechanisms, which combine surface charger transfer phenomena with induced electrostatic potential difference, is characterised by structural simplicity, superior energy transformation performance, and economic feasibility (Liu et al., 2023; Moreira et al., 2023; Yang et al., 2025). These devices demonstrate exceptional consistency and provide seamless operational stability across diverse ambient parameters (Yang et al., 2025). Consequently, TEGs, TENGs, PV, BFC, and PEH have developed into a sustainable approach for capturing biomechanical motions and industrial equipment alternations, along with atmospheric and oceanic dynamic distinctions, successively generating usable electrical output (Han et al., 2023; Rahimi Sardo et al., 2022). They can be used in applications such as wearable electronics, self-powered sensors, etc (Ma et al., 2023; Yang et al., 2025). Since textiles are a basic human need, textile materials must be incorporated into wearables to provide unique functionalities. In the nascent age, textiles were mainly used for apparel and aesthetic purposes, and gradually expanded to household and domestic applications. Textiles were used for technical applications such as military tents, sailcloth, ropes, and garments, which enhanced their properties to provide additional technical performance advantages (Tseghai et al., 2021; Tseghai et al., 2020). These materials and structures can be fabricated into wearables to provide specialised functions and high-level intelligence (e.g., sensing and reacting to environmental stimuli), such as those from thermal, mechanical, chemical, magnetic, and other sources (Simegnaw et al., 2021; Tseghai et al., 2020). Textiles are seamlessly integrated into wearables through weaving and knitting, embedding conductive yarns directly into fabric structures (Y. Chen et al., 2023; Huang et al., 2015; Lam et al., 2022). On the other hand, coating and printing techniques deposit functional nanomaterials and conductive inks onto textile surfaces, allowing energy harvesting and sensing without compromising flexibility and comfort (Eghan et al., 2023; Guérineau et al., 2025; Jiang et al., 2021; Jin et al., 2023; Shahariar et al., 2019).

5 | INTEGRATION OF ENERGY STORAGE SYSTEMS AND BATTERIES

The demand for energy systems in human society has seen a persistent proliferation recently (Weiru Wang et al., 2024), controlling the cost of electricity, replacing ageing systems and infrastructures, improving the flexibility and reliability of power systems, mitigating changes in the atmospheric environment, reducing carbon dioxide emissions, and providing reliable power support to smaller devices (Abdalla et al., 2021; Barrera-Singaña et al., 2025; Materi et al., 2021). Energy storage systems (ESS) that adopt clean energy, which meet the requirements for carbon emission reduction, have been established dynamically over the years (Abdalla et al., 2021). ESSs may experience issues of intermittency and randomness, resulting in voltage and frequency fluctuations (Abdalla et al., 2021; Gaudard & Madani, 2019; Wong et al., 2019). Renewable energy output is intermittent and volatile, which is not conducive to the steady operation of the power network and severely interrupts the integration of TEGs, TENGs, PV, BFC, and PEH systems into wearables. The issue of voltage and frequency fluctuations becomes more prominent as renewable energy mechanisms develop. However, the intrinsic intermittent and inconstant nature of renewable energy sources affects the performance and dependability of the distribution network due to excess generation in electricity at one point in time and a lack of generation at another time (Arul et al., 2015; Castillo & Gayme, 2014; Wong et al., 2019). In light of these challenges, flexible textile-based super capacitors have exhibited great potential for use in wearable systems due to their flexibility, lightweight, ease of integration into textile materials, and their high performance (Islam et al., 2022; M. Li et al., 2022).

Supercapacitors (SCs) are promising electrochemical energy storage devices that can be charged and discharged within seconds and possess high power density, long lifespans, and exceptional cyclic stability (Islam et al., 2022). SC spans a wide range from batteries to conservative capacitors. The integration of malleable conductors and substrate materials into SCs provides structural flexibility, which is highly attractive for a wide range of emerging portable and lightweight consumer devices (Du et al., 2020; Islam et al., 2022; Luo et al., 2020; Pu et al., 2018). Comparatively, SCs are bendable, foldable, and rollable, and can take advantage of the space that may be inaccessible to conventional SCs (Luo et al., 2020; Zhang et al., 2015), making them an ideal alternative electrical substrate for wearable textile electronics. SCs provide seamless, sustainable power for electronic components in wearables without compromising comfort, flexibility, or convenience (Liu et al., 2019). To provide an uninterruptible power supply for wearable textile electronics, it is therefore imperative to consider the fabrication of self-charging power systems (energy-harvesting and energy storage devices) through a circuit management system, which can make environmental energy simultaneously scavenge and store for a self-sustainable

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power supply (Dong & Wang, 2021; Lau et al., 2019), as shown in Figure 8. Wearable textile electronics can achieve energy autonomy by being self-powered and integrating comfortable energy storage devices such as supercapacitors, including carbon nanotubes, graphene-coated textiles, mxene-coated textiles, activated carbon fibre, and hybrid textiles (Inman et al., 2023; Islam et al., 2023; Lu et al., 2017; Yong et al., 2024; Zhai & Chen, 2022; P. Zhang et al., 2024).

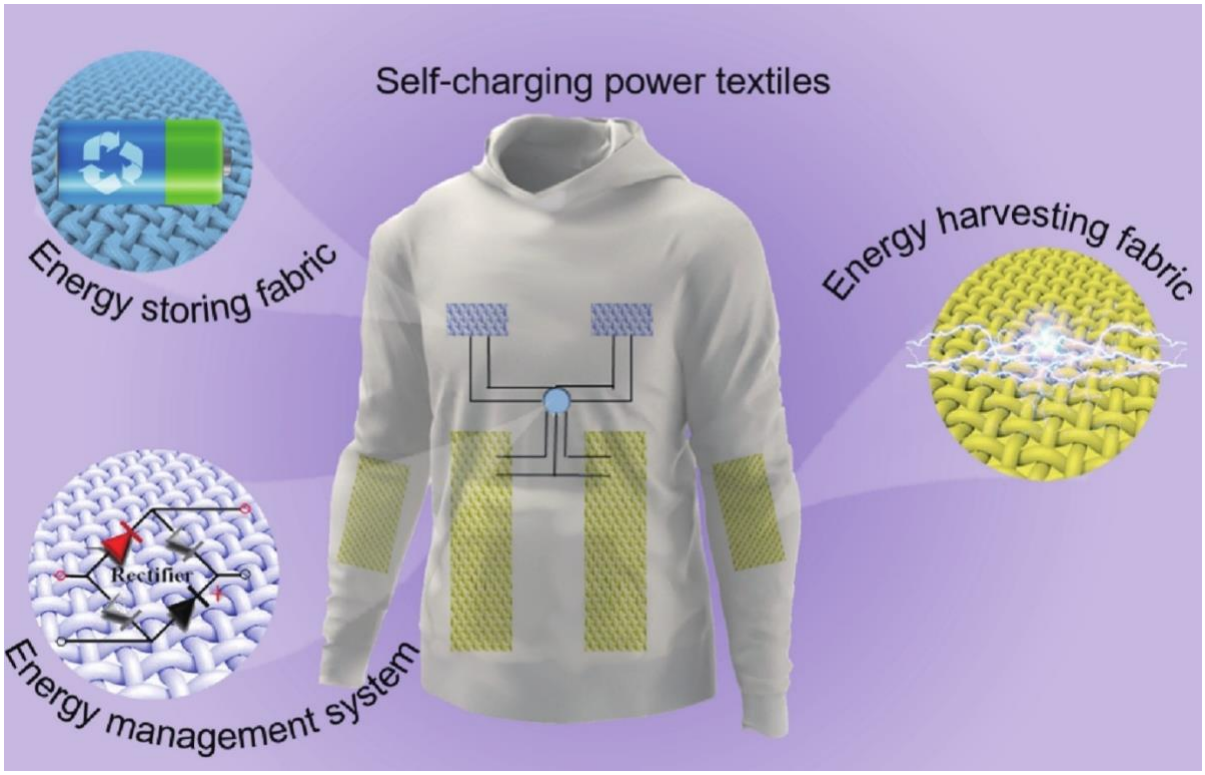


Figure 8. Schematic illustration of self-charging power textiles. It outlines energy harvesting units, power management circuits, and energy storage units that are made of fibre (Dong & Wang, 2021).

5.1| Textile-Integrated Energy Storage Devices

A textile-based energy harvester is an innovative technology for converting ambient energy into electrical energy, serving as a source of energy for remote applications (Amarnath et al., 2025). Textiles (flexible materials) with exceptional properties make them excellent for integrating electronic components in therapeutic and real-time applications. Silver mesh fabrics, activated carbon and carbon fibre yarn, MXene-based fabrics, carbon nanofibre composite, high stretch flexible graphene, and flexible cotton super-fibre have been evaluated to be physically, chemically, mechanically, and physiologically strong, with their optical properties transducing into measurable electrical signals using actuators, sensors, and other conductive components (Sharma et al., 2026). MXene-based textile supercapacitors, laser graphene supercapacitors, Polypyrrole-MXene coated textile supercapacitors, textile fibre-based lithium-ion, and yarn-type asymmetric supercapacitors integrated into textiles provide efficient energy storage, power supply, sensing, tracking of physiochemical signals, and processing and communicating information in real-time (Inman et al., 2023; Yan et al., 2018; Yu et al., 2022). Studies have shown a significant capability of textile-integrated energy storage devices fulfilling non-invasive, accurate, and dynamic functionalities in diverse areas such as health monitoring, military, and sports (Guru et al., 2023; Yu et al., 2022). With the recent development of cutting-edge flexible batteries with high energy density and long lifespans, researchers and developers have been keen on providing batteries that are more flexible and highly deformable, such as bendable, stretchable, and foldable. The recent development has seen these energy storage devices in lightweight, high stability, and good electrical performance (Yan et al., 2018).

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5.2| Power Management and System Integration in Wearable Energy Harvesting Textiles

The current paradigm of wearable devices and their communication networks is infiltrating every corner of contemporary society and transforming every aspect of human life. The tremendous progress of digitalisation and its growing significance to psychological and physical well-being has had a profound impact on consumers and industries globally (Hossain et al., 2022). The swift progress of portable electronics systems in wearable energy harvesting textiles has impressively enriched the various approaches people communicate with each other and their surrounding environment, providing more convenience and accurate information inside human bodies and from the surrounding environment (Yang et al., 2020a). The integration of energy harvesting from human motion (piezoelectric nanogenerators), photovoltaic textiles, thermoelectric fibres, triboelectric nanogenerators (TENGs), and flexible supercapacitors and lithium-ion batteries has demonstrated the potential for storing power, ensuring a steady power supply for wearable healthcare devices, and providing sustainable power applications for automation and health monitoring (Kang & Yeo, 2024; Khan & Khan, 2022; Zhang et al., 2025). Table 3 presents textile-integrated supercapacitors which exhibit a wide range of performance metrics based on electrode materials and fabrication techniques. Silver mesh fabric and activated carbon and carbon fibre yarn achieved 266.6 F g^{-1} and 45.2 mF/cm with 95.4% and 86.6% with retention after 5,000 and 10,000 cycles, while MXene-based fabric achieved ~1000 mF/cm^2 with exceptional flexibility and carbon nanofibre composites exceeding 5,600 mF/cm^2 with ~85% retention at 5,000 cycles (Ghouri et al., 2020; Grube et al., 2024; Iravani & Varma, 2023; Khan et al., 2023; Sundriyal & Bhattacharya, 2020).

Table 3. Performance Comparison of Textile-Integrated Supercapacitors

Device / Electrode Type	Areal Capacitance	Energy / Power Density	Cycle Life / Retention	Fabrication Route	Reference
Silver mesh fabric SC	266.6 F g^{-1}	37.0 Wh kg^{-1}, 177 W kg^{-1}	95.4% @ 5,000 cycles	Embroidery mesh structure	(Khan et al., 2023)
Activated carbon & carbon fibre yarn SC	45.2 mF/cm	~6.5 µWh/cm, ~27.5 µW/cm	~86.6% @ 10,000 cycles	Chemical deposition, polymer gel	(Grube et al., 2024)
Activated carbon/cotton printed SC	430 mF/cm^2	N.R.	~92% @ 10,000 cycles	Screen printing + dip coating	(Grube et al., 2024)
MnO_2–$NiCo_2O_4$//rGO hybrid textile SC	2.12 F/cm^2	37.8 mW/cm^3, 2,678.4 mW/cm^3	Good cycle life	Printing on bamboo fabric	(Sundriyal & Bhattacharya, 2020)
MXene-based all-solid fabric SC	~1000 mF/cm^2		Long-term mechanical flexibility	MXene fabric integration	(Iravani & Varma, 2023)
Carbon nanofiber composite SC (ACFF/PANI/CNT)	5611 mF/cm^2	185 µWh/cm^2, 4,517 µW/cm^2	~85% @ 5,000 cycles	Polymerization + coating	(Grube et al., 2024)
High-stretch flexible SC (graphene/MnO_2)	138.8 mF/cm^2		~87.6% after bending/1000 cycles	Capillary + in-situ growth	(Z. Li et al., 2021)
Flexible SC (CNT cotton super-fibre)			Up to 35,000 cycles	Dip + drying on CNT cotton	(Ghouri et al., 2020)

5.3| Textile Wireless Power Transfer

In addition to energy harvesting, emerging textile-based wireless power transfer systems (textile-based inductive coils, meander coils, liquid-metal coils, coated textile induction systems, and textile-based rectennas) offer a complementary approach for reliable energy delivery (Lee et al., 2022; Micus et al., 2021). These systems generate strong magnetic fields that are localised to the skin surface, enhancing safety and efficiency. The use of low-loss conductive yarn in the textile meander coil design to achieve energy efficiency and lightweight integration into wearable materials. This technology is a

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foundational layer for applications such as augmented reality, health monitoring, and human-machine interaction systems (Rahman et al., 2024). These systems can provide a convenient source of wearable electronics. It uses electromagnetic induction, enabling contactless power transfer, reducing the need for bulky batteries, and enhancing the comfort and aesthetic appeal of smart textiles. The technology simplifies the integration of electronic functionalities into clothing and addresses the challenges of power supply for wearable devices, as the need for lightweight, flexible power storage solutions is on the rise (Cupal et al., 2020). Consequently, textile-based wireless power transfer systems must balance efficiency with safety, as surging transmitted power and operating frequency can improve coupling efficiency but also elevate tissue absorption, requiring compliance with specific absorption rate limits and careful management to prevent heating ("Guidelines for Limiting Exposure to Electromagnetic Fields (100 kHz to 300 GHz)," 2020; Sample et al., 2010). In a practical context, wireless power transfer designs often operate at moderate power levels and optimise coil geometry and alignment to maintain safe on-body performance while minimising efficiency losses (Zhadobov et al., 2011). Moreover, the SAR levels are averaged over a specific mass, typically 10g for European regulations and 1g for North American regulations. The principal concern is the potential for thermal effects, as absorbed energy can raise body temperature. SAR testing helps identify whether a particular device emits RF energy at levels that may contribute to thermal effects, ensuring the safety of electronic devices for human health (Guido & Kiourti, 2020; Yadav et al., 2020).

5.4| Integrated Design Framework modalities for Specific Garment Categories

The proposed design modalities in Table 4 are informed by previous studies undercoring that energy harvesting performance in wearable systems is strongly controlled by power demand, environmental conditions, and user activity profiles, requiring application-specific modality selection and hybridisation strategies (Rong et al., 2021).

5.5| Durability, Washability, and Reliability of Textile-Integrated Energy Systems

The durability, washability, and reliability of textile-integrated energy systems are crucial factors for their successful implementation in various applications. The integration of electronic components into textiles poses unique challenges due to the risk of electrical components being damaged during washing. However, recent developments have improved durability and reliability, with existing studies revealing that electronic yarns can withstand machine washing with minimal failure (Rotzler, von Krshiwoblozki, Kallmayer, & Schneider-Ramelow, 2025). The integration of protective micro-pods and adherence to consistent manufacturing standards are key to achieving reliable e-textiles (S. Lee & S. Park, 2024). The washability of electronic textiles is a vital concern, especially for textile-integrated circuits that are permanently attached to the textile substrate. Research indicates that up to 100 wash cycles can be performed on various textile circuits, showing vulnerabilities and the need for optimisation to improve washability (Shahidi et al., 2025). The study indicates that well-encapsulated devices can retain approximately 75-90% of their initial performance after 10-50 washing cycles, illustrating that performance degradation remains highly dependent on material selection and enclosure strategy, and integration level (Azani & Hassanpour, 2024). The fabrication techniques for electronic textiles, such as the use of conductive yarns and their insertion into textiles using traditional techniques, or the application of conductive coatings directly onto existing textiles, have been scrutinised. The techniques are very significant for ensuring the durability and functionality of electronic textiles during everyday processes (frequent use and washing) (Liu et al., 2026). Durability and washability of wearable energy systems are increasingly assessed using standardised textile testing protocols such as ISO 6330 for perspiration exposure, laundering, abrasion resistance, and flexing tests (Suhyun Lee & Sohyun Park, 2024; Rotzler & Schneider-Ramelow, 2022; Veske et al., 2020; Washing, 2021). These standardised metrics are significant for benchmarking real-world applicability and long-term reliability (Tan, 2022).

Table 4. Integrated Design Framework for Energy Harvesting in Wearable Systems

Garment Category / Use Case	Power Budget	User Activity Level	Environmental Conditions	Textile Structure / Integration	Recommended Modality	Design Rationale	References
Office wear / Smart casual	Low (10–1000 μW)	Sedentary/light motion	Indoor lighting (200–1000 lux), low ΔT	Fabric-level (laminated layers)	Indoor PV + RF harvesting	Stable indoor light; minimal motion limits mechanical harvesting	(Rong et al., 2021)
Healthcare wearables	Ultra-low to low (<100 μW)	Minimal/passive	Body heat (ΔT ≈ 3–5 °C), indoor	Fibre/yarn integration	TEG + low-power PV	Continuous passive energy from body heat; suitable for long-term monitoring	(Nozariasbmarz et al., 2020)
Sportswear / Fitness apparel	Moderate (1–100 mW)	High activity (1–3 Hz motion)	Outdoor/indoor mixed	Yarn/fabric embedded systems	TENG + Piezoelectric	High mechanical deformation enables efficient motion-based harvesting	(Li et al., 2024; Y. Wang et al., 2023)
Outdoor workwear	Moderate to high (10–100 mW)	Moderate activity	Strong sunlight (~1 sun), variable motion	Fabric/garment-level integration	PV + TENG (hybrid)	Combines dominant solar input with supplementary motion energy	(Vahidhosseini et al., 2025; Yu et al., 2024)
Military / Field gear	High (>100 mW)	Variable (low to intense)	Harsh/variable (sunlight, motion, temperature gradients)	Garment-level modular systems	Hybrid (PV + TENG + TEG + storage)	Ensures reliability and redundancy under unpredictable conditions	(Vahidhosseini et al., 2025; Yu et al., 2024)
Smart fashion / Consumer wearables	Low to moderate (10 μW–10 mW)	Light to moderate	Indoor + intermittent outdoor	Fibre/yarn/fabric hybrid integration	TENG + PV	Balances aesthetics, flexibility, and intermittent energy sources	(Rong et al., 2021; H. Zhang et al., 2024)

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6 | CHALLENGES AND RESEARCH GAPS

Wearable technology and textile electronics are still in their initial stages, with numerous drawbacks (Gunawardhana et al., 2022; Gunawardhana et al., 2020). Several challenges persist in the quest to harvest energy for wearable textiles. One of the major challenges lies in the scalability and mass production (Gunawardhana et al., 2022). Laboratory models have proven promising performance, but transforming these results into large-scale, individual manufacturing products remains a significant hurdle. The available fabrication techniques (advanced coating process and nanostructuring) are not yet optimised for high-throughput production (Beeby et al., 2025; Dolez, 2021; Y. Li et al., 2022). It creates irregularities in device performance and hampers the reliability of wearable systems in real-world applications (Gunawardhana et al., 2022). To achieve scalable fabrication, it requires advancements in textile production techniques that preserve energy, foster resilience, and enhance flexibility at industrial capacities (Dolez, 2021; Rafique et al., 2023; Seyedin et al., 2021). In addition, standardisation and testing protocols remain a major obstacle for wearable textile electronics. At the moment, there is no universally approved framework which can be used to evaluate the performance, safety and reliability of wearable harvesting textiles in this modern era, where computerisation and AI are more advanced (Rotzler et al., 2021; Rotzler & Schneider-Ramelow, 2022). The devices are frequently tested under diverse experimental conditions, rendering it difficult to compare their efficiency, durability, and user comfort (Rotzler, von Krshiwoblozki, Kallmayer, & Schneider-Ramelow, 2025). Washability tests, mechanical durability, biocompatibility, and standardisation protocols for performance evaluation are required to accelerate its implementation and build trust within industries such as healthcare, sports, and defence. The establishment of standards will ensure the integration of energy harvesting textiles into regulated sectors and avoid substantial disruptions (Rotzler & Schneider-Ramelow, 2022; Rotzler, von Krshiwoblozki, Kallmayer, & Schneider-Ramelow, 2025).

Nevertheless, the environmental impact and end-of-life disposal of these novel technological devices raise crucial alarms (Gwenzi et al., 2018; Wenyu Wang et al., 2024). Its reliance on rare-earth elements, polymers, and nanomaterials may pose toxicity and recycling challenges (Saleem & Zaidi, 2020; Ewa Skrzetuska & Paulina Rzeźniczak, 2025). In our contemporary times, there has been insufficient research to understand the long-term environmental footprint of discarded wearable electronics, particularly as consumer use scales up. Producing eco-friendly and biodegradable alternatives is essential for aligning wearable energy harvesting with international sustainability objectives and circular economy principles (Chen et al., 2022; Y. Li et al., 2021; E. Skrzetuska & P. Rzeźniczak, 2025). High costs and commercial feasibility remain significant challenges. Though existing models demonstrate significant potential, complex production processes and advanced materials often lead to high costs, hindering market adoption. Wearable energy harvesting textiles must integrate performance, cost-efficiency, and comfort to attain sustainability (Ivanoska-Dacikj et al., 2024). Minimising production expenses, showcasing consistent long-term efficacy, and enhancing material accessibility are crucial for garnering commercial investment and consumer trust (Paravannoor, 2023). Researching into hybrid systems that integrate several energy harvesting mechanisms may perhaps improve efficiency while saving costs (Tohidinejad et al., 2024).

6.1| Standardisation, cost-effectiveness and environmental sustainability of wearable textile electronics

Standardisation, environmental sustainability, cost-effectiveness, and health and safety risks have not received much attention in the field of wearable harvesting technologies. Safety considerations and incidents related to worker safety and working conditions can delay the disposition of novel technology if risks are not well communicated and managed (Cavaliere, 2023). Worker safety is a priority for most advanced industries, as illnesses, injuries, and deaths often cause substantial financial losses, a series of dismissals, government checks, and loss of company reputation (Svertoka et al., 2021). Statistics indicate that the number of worker-safety accidents per year has drastically decreased due to proper workforce regulation and standardisation. Wearables raise ethical and regulatory challenges regarding data privacy, especially in the health sector. As electronic wearables collect, process, store, and share a significant amount of data, which may be accessed by third parties, this practice is very unprofessional, as health data is sensitive and confidential by nature (Bouderhem, 2023). It is recommended that public and private actors, stakeholders, and government agencies find a consensus and acceptable balance between regulation and innovation. It has been noted that there are no documented standards for wearable textile electronics. Though technical, ethical, and regulatory challenges persist, data security, data quality,

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interoperability across different operating systems, health equity, and fairness need to be addressed globally. Standardised national and international regulations should be established. Environmental sustainability of wearable textile electronics is a significant concern in the industry. Studies indicate that electronic textiles can be sustainable and biodegradable, providing a real-life solution to the environmental impact of traditional electronic textiles (Dulal et al., 2025).

7 | CONCLUSION AND FUTURE STUDIES

This review underscores the substantial progress and achievements in wearable textile harvesting, with technologies such as piezoelectric nanogenerators, photovoltaic cells, triboelectric nanogenerators, and thermoelectric generators emerging as viable power-supply solutions for smart textiles. The key findings reveal that these systems provide promising efficiency and adaptability. From a sustainability and innovation perspective, wearable energy harvesting reduces reliance on conventional batteries and aligns with global objectives for implementing eco-friendly technology. Advances in materials science, hybrid integration, and production techniques continue to drive improvements that boost performance and comfort. To overcome current obstacles and realise workable, scalable, and sustainable solutions for the upcoming generation of wearable technologies, the future of this field hinges on strong interdisciplinary collaboration across materials science, engineering, textiles, healthcare, and environmental studies. It is worth acknowledging the growing number of energy-harvesting technologies and the need to identify those with a resilient future outlook. It is therefore essential for researchers, developers, investors, and policymakers to provide adequate resources to develop these diverse technologies. There is also a need for guidelines for technology managers and investors to establish applicable metrics that assess these technologies for their prospective future success. Managers must prioritise investment in safe, cost-effective, and scalable energy harvesting and storage technologies that can be seamlessly embedded into textile manufacturing processes. The findings of this study indicate the need for cross-functional collaboration among materials textile engineers, material scientists, and product designers to accelerate commercialisation and ensure regulatory compliance, long-term sustainability, and user comfort for wearable textile products. Wearable technologies such as thermoelectric nanogerators and nanogenerators are advancing rapidly, with current research focused on improving their commercial viability and efficiency.

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DATA AVAILABILITY STATEMENT

This study is a review article; therefore, all data supporting the findings and discussions are contained within this manuscript. No additional datasets were generated or analysed during the current study.

ETHICAL APPROVAL STATEMENT

There is no ethical approval for this study, as it is a review paper with all data extracted from secondary sources.

CONFLICT OF INTEREST STATEMENT

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this article.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this manuscript, the authors used Grammarly to check, modify, and enhance clarity and quality of the grammar and spellings. All research design, data collection, analysis, interpretation of findings, and conclusions were developed by the authors. After using this tool, the authors carefully reviewed and edited all suggested text and take full responsibility for the accuracy and integrity of the manuscript.

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