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Review Article

# Sustainable Materials for Energy Harvesting and Storage: A Review of Emerging Trends and Technologies

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**Abstract**

Amidst the global energy crunch, the widespread prevalence of major climatic disruption and extreme weather requires a wholesale systemic disruption of incumbent fossil fuel infrastructure. As the world seeks to effectively decouple economic development from its concomitant carbon emissions footprint, a growing concern within modern materials science is the replacement of depleted high-toxicity elements with earth-abundant, circular alternatives. As a result, modern sustainable materials design is now acknowledged as the most critical bottleneck for efficiency levels in decentralized clean power architectures. This field now sees various new energy harvesting approaches, including lead-free perovskite photovoltaics, triboelectric nanogenerators and flexible bio-based piezoelectric matrices that harness local energy sources through clean mechanisms. The chaotic electrical signals provided from these mechanisms can be reliably stored with modern high energy capacity batteries such as sodium-ion cells and rapidly charging pseudocapacitors. While these systems show immense potential for cleaner energy harvesting, mass adoption is currently stymied by problems associated with biomass inconsistencies, poor high-strain stability and the high cost of starting manufacture. The viability of these new energy approaches hinges entirely upon the future integration of machine-learning algorithms that promote novel low-toxicity materials and combined self-powered units. It is our intention to map the route for all relevant research efforts, from the laboratory stage to sustainable industrial power generation, through the information presented herein.

**Keywords:** Sustainable materials; Energy harvesting; Electrochemical energy storage; Green electronics; Self-powered systems; Circular materials design

## Introduction

Energy systems globally are currently under immense stress due to rising demand, speedy industrialization, global population expansion and continued exploitation of fossil fuels thereby jeopardizing the very sustainability of traditional energy infrastructures (Zheng et al., 2023; Adamczyk et al., 2024). The pressures, however, have been magnified over time due to frequent geopolitical conflict, economic instability and the various global shocks in the fossil fuel supply chains which in turn has put the old energy systems to the test when unanticipated disruptions occur and causes fuel prices to skyrocket (Popescu et al., 2025). Providing sustainable and affordable energy to all countries in order to boost societal development remains therefore one of the core objectives that governments, industries and researchers around the globe aspire to and this has culminated into an ongoing and swift transformation towards clean and secure energy systems (Bdrcea et al., 2026).

The reliance of decades of use of fossil fuels has substantially escalated levels of green-house gases leading to global heating, the extinction of plants and animals, degradation of natural resources and ecosystems, in addition to increased number of natural calamities in recent decades that directly threaten both the environment and society at large (Sarkodie & Osei, 2026). Climate change has also led to renewed impetus for global action towards carbon neutrality, spurring an increased global interest in research on and investment in solar, wind, hydro, and biomass resources in an attempt to meet an escalating energy demand with less carbon emissions (Green et al., 2024). Yet despite progress in such innovative devices renewable sources can generate only limited amounts of electricity, because they depend heavily on the weather and changing seasons. So even with modern harvesting techniques electricity can only be produced sporadically, affecting the availability of uninterrupted power to homes and infrastructure (Kim and Lee 2025). Hence alongside advanced harvesting technologies with new kinds of electrode and device structures it is essential to develop highly effective methods for storing any harvested electricity for later use.

According to Chen and Lin (2025) for modern power devices most factors defining the characteristics of power devices rely on the performance of energy storage materials. Some promising candidates of nanostructured sustainable materials such as bio-inspired polymers, multifunctional composites and novel architecture provide combined electrical and mechanical properties, high stability of thermal and chemical environment and eco-friendly characteristics and other materials such as biomass derived materials, carbon-based structures, and interfaces engineering have attracted considerable attention to improve the charge transportation, dielectric properties, electrochemical behavior, and stability performance for a wide range of sustainable applications, together with reduce the use of resource depleted materials (Chen and Lin 2025; Gao and Zhang 2025, Silva et al. 2025).
Furthermore, it is also of great significance to integrate the energy harvesting and energy storage techniques to build an entire system to make maximum use of energy. By harvesting ambient energy (solar, thermal, vibration, mechanical energy etc.), it can convert energy into electrical power, and the storage element is needed to store electrical power when fluctuating supply occurs and maintain the continuous power for operation (Li & Wang, 2026). Advanced material and intelligent management systems (power management) can further improve the energy efficiency of conversion, reduce energy loss of transmission, and promote power of wearables, wireless sensor network, electric vehicle, smart infrastructure etc. (Martinez et al., 2024; Anderson et al., 2025).

Sustainable material and scalable engineering technique can pave the way for large-scale application and market entry and reinforce our resilience towards global energy crises (Garcia et al., 2026). This paper intends to systematically review the recent development in the sustainable material towards integrated energy harvesting and energy storage, including material design, working mechanisms, engineering approaches, technical challenges and prospect for further investigation that will realize the more efficient and sustainable and scalable energy generation, collection, storage and utilization systems.

**Sustainable Functional Materials for Energy Technologies**
**Classification of Sustainable Energy Materials**

In fact, the categorization of sustainable energy materials relies on their intrinsic chemical formulation, macrostructural topology, and processing life cycle (Kumar et al., 2024). Thus, enabling novel harvesting and storage devices needs to intrinsically address the displacement of anthropogenic hydrocarbon feedstocks to entirely new groups of materials, that have different properties to those currently widely exploited, and which are sustainable (Gao & Zhang, 2025). To guide the rational selection of appropriate chemical building blocks and their integration, for devices such as for clean electronics, a modern material taxonomy can define broad categories of materials used in functional device platforms, as summarized here: bio-based materials, carbon-based materials, conductive polymers, ceramic materials, nanocomposites and multi-component hybrid systems (Kumar et al., 2024). This hierarchy of these configurations is summarized in conceptual form in the underlying core materials taxonomy, presented in Figure 1.

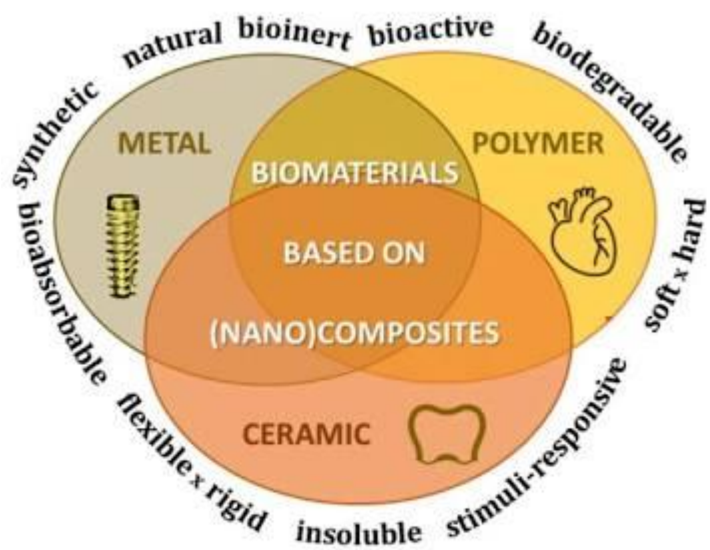


**Figure 1. Classification of sustainable materials for energy harvesting and storage**

**Source: Kumar et al. (2024)**

Beneath each material group a range of specific chemical properties and sustainability opportunities for device construction are provided (Silva et al., 2025). Bio-based resources such as cellulose and chitin present ideal surface hydroxyls for modification, low-toxicity processing and unrivaled structural degradability (Silva et al., 2025), whilst the high thermodynamic stability of the readily accessible inner pore surface area is afforded by carbon-based materials such as biomass-based biochar and activated carbon (Gao & Zhang, 2025). Conductive polymers combine intrinsic organic flexibility and electronic mobility by providing a pathway for electrons to propagate through conjugated molecular backbones (Kumar et al., 2024) whereas advanced ceramics and metal oxides enable long-term mechanical durability and large dielectic constant capability for harsh environments (Wang & Liu, 2026). Novel composites or hybrid systems bring together multiple categories in order to harness combined properties which outperform individual material classes (Wang & Liu, 2026).

**Structure–Property Relationships**

The success in optimizing energy harvesting and storing efficiency relies fully on a deep understanding of structure-property relationships inherent to the material matrix (Martinez et al., 2024). Atomic and structural features such as crystalline arrangement, inherent porosity, electric conductivity, mechanical compliance and available surface area will define the performance limitations (Nguyen & Tran, 2025). Crystal phases and precise lattice constants allow for optimum charge separation and movement at the active material surface (Martinez et al., 2024). Higher electrical conductivity inhibits further loss of energy (Xie et al., 2025) while flexibility guarantees robust mechanical stability during the cyclic movements in wearable devices, preventing the structural decomposition of the device (Nguyen & Tran, 2025). The step-by-step structure-property path from material properties to device performances is schematically illustrated in Fig. 2.

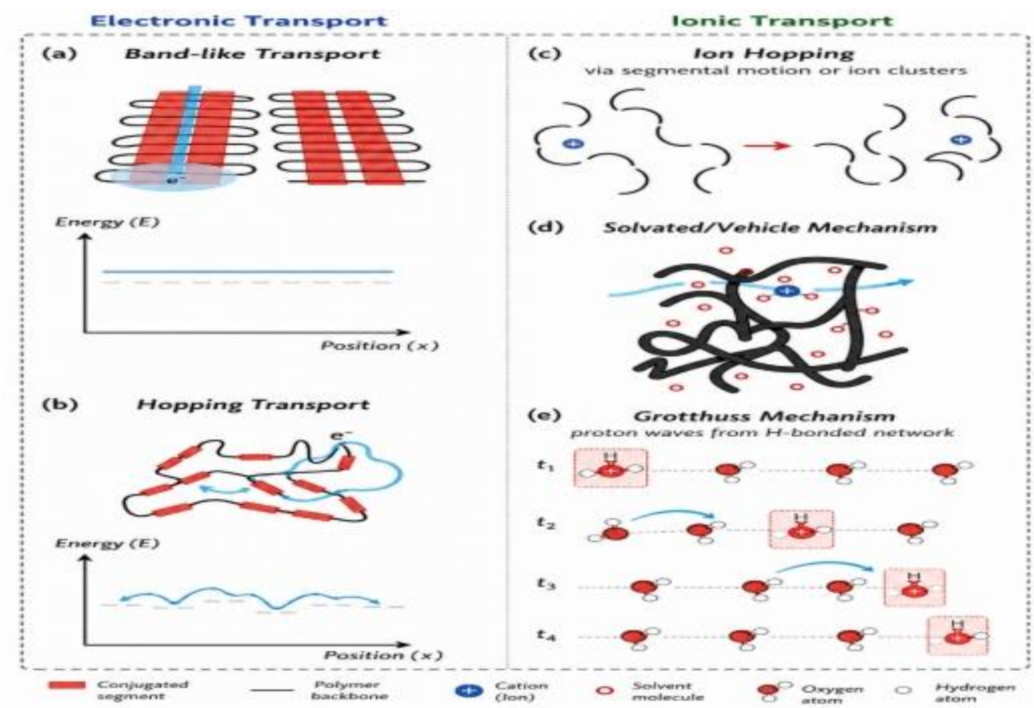


**Figure 2. Relationship Between Material Structure and Functional Properties**

**Source: Martinez et al. (2024) Nguyen & Tran, (2025).**

Understanding how material engineering governs device performance requires a close look at these molecular transport pathways (Xie et al., 2025). According to Xie et al. (2025), tailoring the local morphology from rigid crystalline lattices to highly open, flexible architectures changes the underlying charge transport mechanisms from simple band-like conduction to rapid ion-hopping modes. This atomic tunability directly dictates the macro-level efficiency of energy conversion and capacitive storage frameworks (Nguyen & Tran, 2025). When structural engineering successfully eliminates charge trap states and minimizes internal resistance, the device achieves much higher power densities and maintains structural integrity across thousands of cycles (Martinez et al., 2024). Ultimately, adjusting these structure-property relationships allows researchers to customize green platforms for specific application environments (Xie et al., 2025).

A comprehensive overview of these sustainable materials, alongside their principal properties and standard application environments, is structured below (Table 1).

**Table 1. Sustainable materials used in energy harvesting and storage**

| Material | Major Properties | Typical Applications |
|---|---|---|
| Graphene | High electrical conductivity, high surface area (Gao & Zhang, 2025) | High-rate supercapacitors and electrode backbones (Gao & Zhang, 2025) |
| Cellulose | Excellent flexibility, mechanical robustness, non-toxic (Silva et al., 2025) | Wearable devices and flexible substrate platforms (Silva et al., 2025) |
| MXenes | High volumetric capacitance, metallic conductivity (Wang & Liu, 2026) | Advanced metal-ion batteries and pseudocapacitors (Wang & Liu, 2026) |
| Conductive polymers | Lightweight, tunable band gap, mechanical compliance (Kumar et al., 2024) | Flexible electronics and organic solar cells (Kumar et al., 2024) |
| Biochar | Highly sustainable carbon source, low cost, porous (Gao & Zhang, 2025) | Commercial battery electrodes and water purification (Gao & Zhang, 2025) |

**Sources: Yamada et al. (2026)**

**Sustainable Materials for Energy Harvesting Technologies**
**Photovoltaic Energy Harvesting**

According to Green et al. (2024), the photovoltaic effect serves as the primary foundational pillar for direct ambient solar energy conversion systems. This conversion pathway begins when light absorption triggers electron excitation across the characteristic semiconductor band gap (Kim & Lee, 2025). Upon capturing these incoming photons, charge generation instantly takes place as bound electrons transition into the conduction band, creating corresponding holes (Green et al., 2024). According to Yamada et al. (2026), implementing sustainable photovoltaic materials is absolutely essential to minimize the carbon footprints historically linked with industrial solar panel manufacturing. The functional sequence guiding this photon-to-electron energy conversion cascade is illustrated in the standard operational framework below (Figure 3).

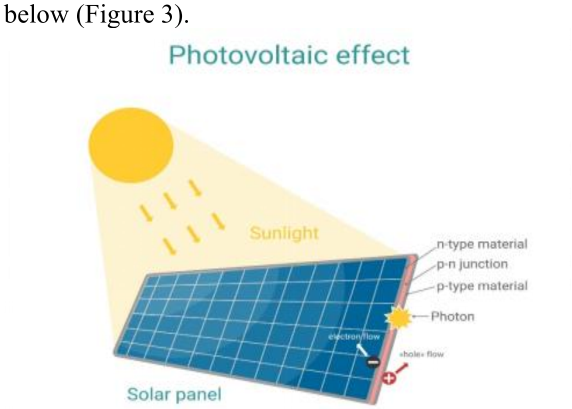


**Figure 3. Mechanism of solar energy harvesting in photovoltaic materials**

Beyond conventional high-purity silicon architectures, recent literature highlights rapid breakthroughs in perovskite, organic, and bio-inspired solar thin-films (Yamada et al., 2026). According to Yamada et al. (2026), lead-free halide perovskites offer exceptional absorption coefficients alongside highly cost-effective, solution-processable synthesis pathways. To push past the theoretical Shockley-Queisser efficiency limits of single-junction devices, advanced tandem photovoltaic configurations stack distinct bandgap layers to capture a much broader swath of the solar spectrum (Green et al., 2024). Furthermore, recent work emphasizes hybrid photovoltaic–thermoelectric setups that structurally integrate thermal cells directly behind solar arrays (Kim & Lee, 2025). According to Kim and Lee (2025), this hybrid architecture captures non-radiative, parasitic waste heat from solar cells, significantly raising the total conversion efficiency of the combined device.

**Piezoelectric Energy Harvesting**

This piezoelectric energy harvesting process is wholly reliant on the implementation of materials that do not contain an inversion center in the crystal structure, as explained by Smith and Jones (2024). In these non-centrosymmetric designs, applied mechanical deformation will cause the instant displacement of ions within the materials resulting in a net electrical polarization, Tanaka and Suzuki (2025). The mechanical strain causes a restructuring in internal bonds that repositions dipoles leading to an instantaneous charge separation that becomes detectable along an electrode surface.

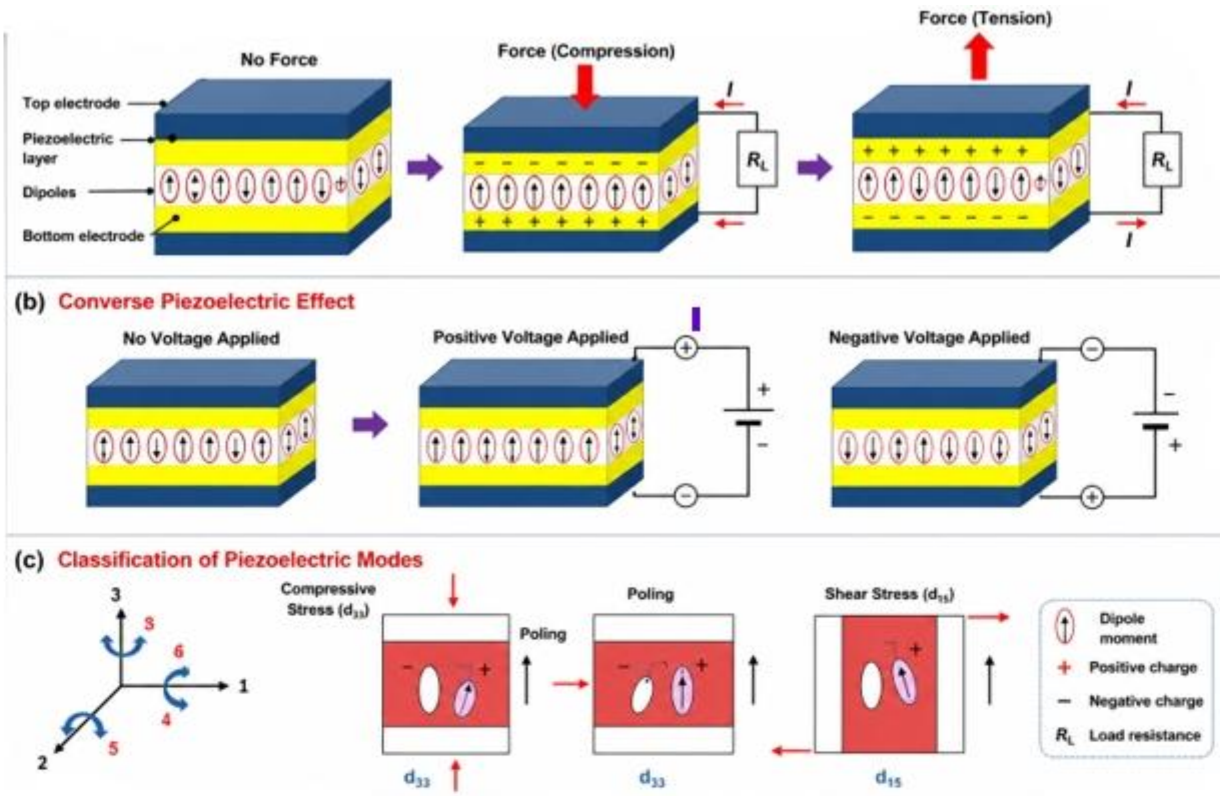


**Figure 4. Piezoelectric energy harvesting mechanism.**
**Source: Smith and Jones (2024)**

When designing components under cyclic loading conditions, considerable variation is made between the utilization of piezoelectric ceramics and polymers (Smith & Jones, 2024). According to Garcia et al. (2026), while ceramics, such as $BaTiO_3$ have high values of piezoelectric coefficient, they are inherently brittle and unsuitable for high-strain applications. Conversely piezoelectric polymers like PVDF are more mechanically compliant, allowing high strain bending without physical destruction (Garcia et al., 2026). In more modern work, researchers are developing flexible matrices which incorporate both material classes (Tanaka & Suzuki, 2025). This is successful at compromising the excellent polarization values of the ceramics with the compliant and low weight organic polymer (Smith & Jones, 2024).

**Thermo-electric energy harvesting**

The direct generation of electricity from thermal energy loss is commonly realized via thermoelectric devices (Rowe et al., 2024). Thermoelectric energy harvesting utilizes the Seebeck effect where by creating a thermal gradient across a conductive medium electrons/holes diffuse from a high-temperature zone to a lower-temperature zone, creating a measurable voltage between terminals (Rowe et al., 2024). The path of the charge carriers which transfer from heat to electricity is traced chronologically in the section below (Figure 5), with efficient energy harvesting relying on optimizing ZT, or figure of merit (Zhao & Wang, 2025).

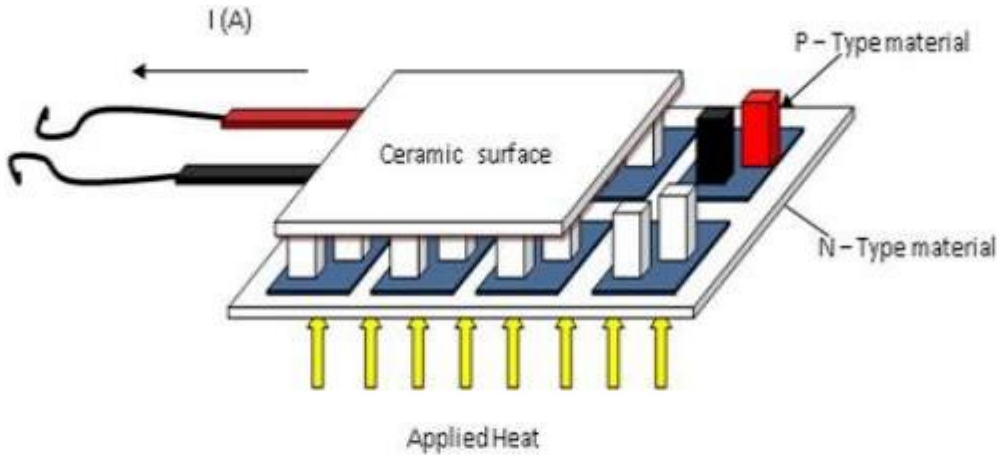


**Figure 5. Thermoelectric energy harvesting pathway**
**Source: Rowe et al. (2024)**

Deploying these systems effectively requires a steady shift toward sustainable thermoelectric materials suitable for large-scale waste heat recovery (Rowe et al., 2024). According to Garcia et al. (2026), conventional thermoelectric devices rely heavily on scarce, toxic elements like bismuth telluride ($Bi_2Te_3$). To replace these problematic alloys, recent work focuses on Earth-abundant silicides, copper oxides, and organic conducting polymers (Zhao & Wang, 2025). According to Rowe et al. (2024), these green alternatives are uniquely suited for industrial waste heat recovery, auto-exhaust harvesting, and localized thermal management. By capturing low-grade thermal waste, these sustainable materials can recycle massive amounts of secondary energy that would otherwise escape into the atmosphere (Zhao & Wang, 2025).

**Triboelectric Nanogenerators**

Triboelectric nanogenerators (TENGs) combine both contact electrification and electrostatic induction in an efficient way (Wang et al., 2024). During the process, electrons are transferred from one surface to the other if they are brought in contact and they possess difference electron affinities, while subsequent movement of their surfaces can result in the generation of a potential difference between them to drive current in an external load (Chen & Lin, 2025). The operation of triboelectric nanogenerators are also ideal for wearable applications, because the power density is high at the low frequencies of the human body movements (Chen & Lin, 2025). Figure 6 depicts the full cycles for a basic triboelectric system.

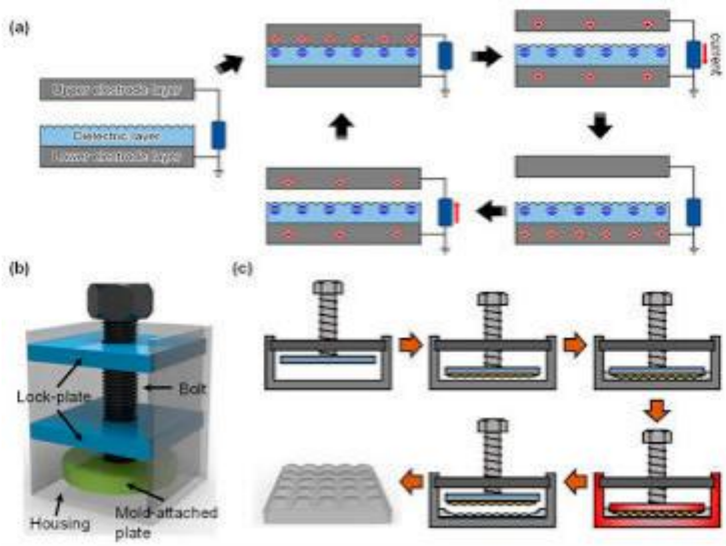


**Figure 6. Working principle of triboelectric nanogenerators**
**Source: Chen & Lin (2025)**

To improve the environmental lifecycle of these devices, modern TENG research prioritizes the integration of biodegradable polymers and flexible components (Wang et al., 2024). According to Garcia et al. (2026), utilizing natural matrices like chitosan, cellulose, and silk fibroin helps prevent electronic waste accumulation. These green polymers undergo surface structural modification via chemical etching or nanoparticle embedding to increase their surface charge density (Chen & Lin, 2025). According to Wang et al. (2024), these flexible, biopolymer-based devices conform easily to human skin and clothing interfaces. Consequently, they provide a highly sustainable, self-powered sensing solution for next-generation biometric and personalized health monitoring applications (Chen & Lin, 2025).

**Table 2. Comparison of major energy harvesting technologies**

| Technology | Energy Source | Sustainable Materials | Advantages | Limitations |
|---|---|---|---|---|
| **Photovoltaic** | Solar/Ambient Light | Perovskites, Organic polymers (Green et al., 2024) | High power density, mature scalability (Green et al., 2024) | Intermittent generation, high initial capital cost (Yamada et al., 2026) |
| **Piezoelectric** | Vibrations, Mechanical Stress | $PVDF$, Barium titanate composites (Smith & Jones, 2024) | High output voltage, works in dark settings (Tanaka & Suzuki, 2025) | Lower current output, brittle ceramic elements (Garcia et al., 2026) |
| **Thermoelectric** | Waste Heat, Thermal Gradients | Earth-abundant silicides, Polymers (Rowe et al., 2024) | Continuous power, no moving components (Zhao & Wang, 2025) | Low conversion efficiencies for low-grade heat (Rowe et al., 2024) |
| **Triboelectric** | Friction, Mechanical Contact | Chitosan, Modified cellulose (Wang et al., 2024) | Exceptional low-frequency efficiency (Chen & Lin, 2025) | Surface material wear, sensitive to moisture (Wang et al., 2024) |

**Sustainable Materials for Energy Storage Technologies**
**Rechargeable Batteries**

Today, leading energy storage is dominated by advanced designs of lithium-ion, sodium-ion, and solid-state batteries. The demands to serve our future energy needs requires a movement away from cobalt-intensive electrode chemistries towards low-cost electrode materials that are derived from rich natural precursors (Olabi et al. 2026). Though the well-established manufacturing industry still supports Li-ion technologies, the alternative of sodium-ion is poised to supply low-cost energy at scale for grid energy storage (Zhang et al. 2025), and solid-state batteries can be used to remove any liquid leakage risk by replacing liquids by solid ion conductors (Ahuja et al. 2024). As explained by Ahuja et al. 2024, operating stability of these batteries is mainly influenced by their structural changes that occur during cycling (figure 7 showing the structural elements of these reversible cells and its transport pathways):

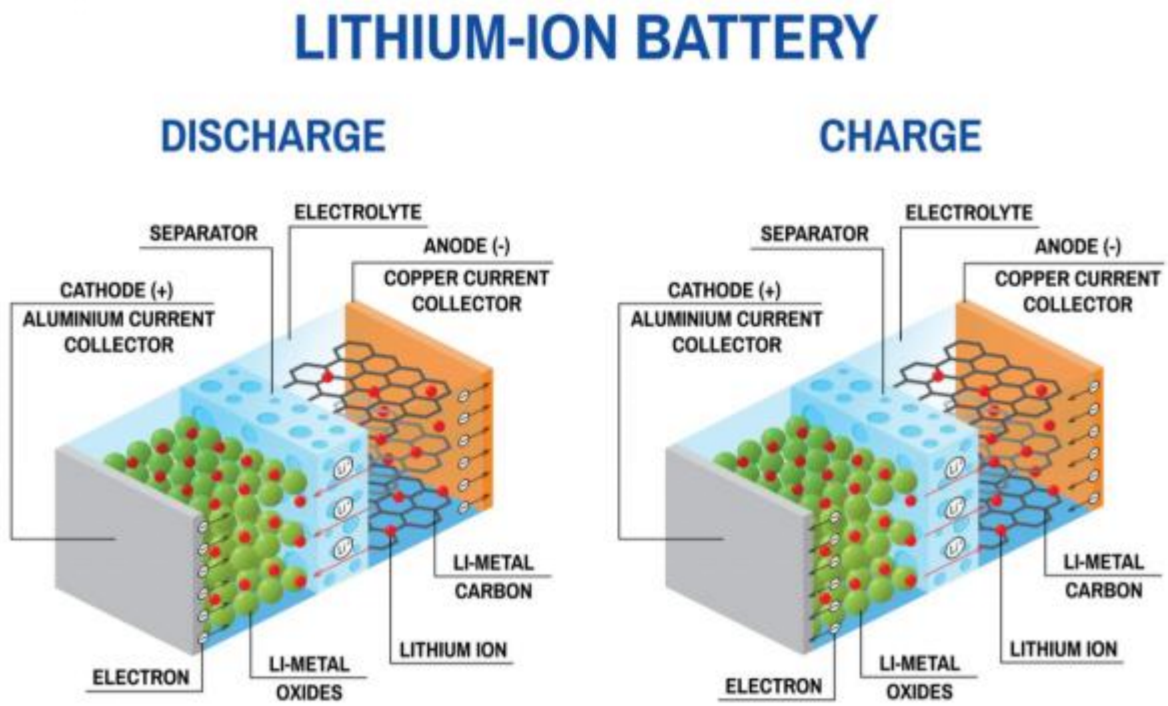


**Figure 7. Charge–discharge mechanism in rechargeable batteries**
**Source: Ahuja et al. (2024)**

Below this physical framework, distinct electrochemical storage mechanisms govern the movement of charge carriers inside the cell matrices (Olabi et al., 2026). According to Olabi et al. (2026), classic intercalation involves the physical insertion and extraction of ions directly into the gaps within guest host lattices. In contrast, conversion and alloying mechanisms involve reversible chemical transformations that yield significantly higher theoretical capacities (Zhang et al., 2025). According to Ahuja et al. (2024), utilizing green polymer binders and biomass-derived carbon anodes minimizes structural micro-cracking caused by large volume changes during operation. Consequently, engineering these sustainable host materials ensures stable, long-term chemical cycling while keeping environmental impacts low (Olabi et al., 2026).

**Supercapacitors**

Burke et al. (2025) described supercapacitors to be indispensable components as power-delivery devices because of their high charge/discharge rates and operational longevity. Supercapacitors store charges through two separate mechanisms: EDLC and Faraday pseudocapacitance (Borenstein et al., 2024). Purely electrostatic adsorption of ions at the boundary between a high surface-area electrode and an electrolyte matrix, known as EDLC, is employed by the first. Pseudocapacitance involves the transfer of electrons that leads to rapid redox reactions.

Researchers have combined the first and second mechanisms of storing energy to realize a system that stores power at a higher density while increasing its energy-storing performance (Wang & Chemical Reviews Open, 2025).

Visually depicting the interface mechanics that distinguish purely electrostatic attraction and structural intercalation, illustrated below.

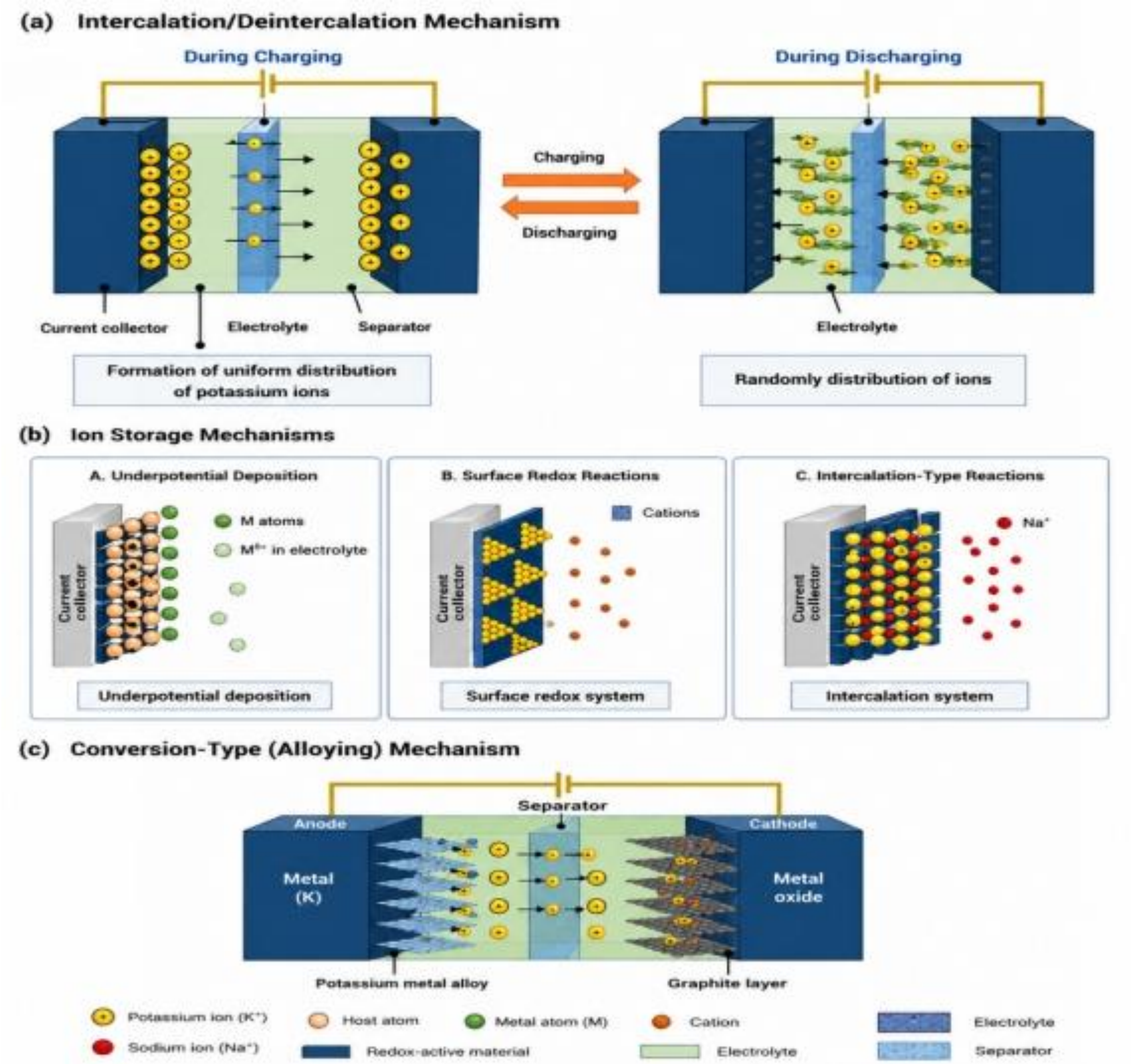


**Figure 8. Charge–discharge mechanism in rechargeable batteries**
**Source: Borenstein et al. (2024)**

By comparing EDLCs with pseudocapacitors in parallel, we see there are different advantages and disadvantages for the performance due to different electrode materials (Burke et al., 2025). The EDLC's use extremely porous carbons such as activated carbon, or carbon nanotubes which provide high cycling stability (e.g. 100k cycles) but limited energy density (Borenstein et al., 2024). Pseudocapacitives materials, such as transition metal oxides and conducting polymers can offer very high specific capacitances due to redox reactions occurring at the surface (Wang & Chemical Reviews Open, 2025) but can suffer more rapid degradations in structure due to rapid changes in volume with chemical volume expansion and contraction during cycling (Borenstein et al., 2024).

## Hybrid Energy Storage System

According to Hannan et al. (2025), the HESS technology utilizes a combination of a high energy density battery system coupled to a rapid delivery system like a supercapacitor,

helping to avoid the limitations that solo energy storage units present (Chodankar et al., 2026). A battery can cater for the long-term stable and ongoing power needs, whilst the supercapacitors deal with rapid bursts of power. To efficiently regulate and manage power distribution between the devices, an advanced power electronics interface is required, preventing system damage (Chodankar et al., 2026). Figure 9 shows an illustration of how the prime harvesting collection units are connected to balanced hybrid storage units in terms of a technical structure.

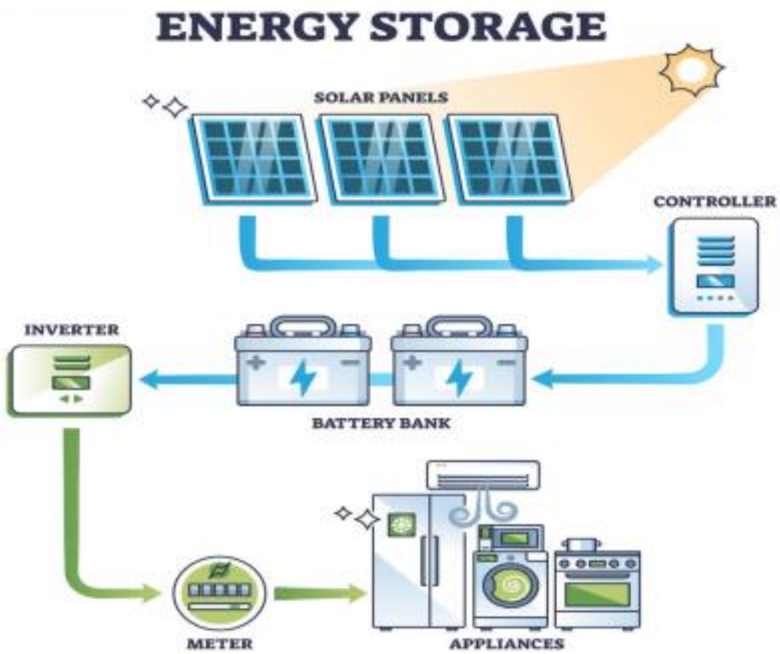


**Figure 9. Hybrid battery–supercapacitor energy storage system**
**Source: Hannan et al. (2025)**

The complementary functions of these two devices ensure enhanced operational efficiency across erratic load cycles (Hannan et al., 2025). According to Chodankar et al. (2026), using the supercapacitor to buffer high-frequency power spikes shields the battery from severe thermal stress and deep discharge cycles. This targeted power division significantly extends the overall operational lifespan of the battery pack (Hannan et al., 2025). Furthermore, this hybrid coupling enables highly efficient regenerative braking energy capture in electric vehicles and smooths out power generation from intermittent renewable grids (Chodankar et al., 2026). Ultimately, building these hybrid architectures using eco-friendly materials represents a vital step toward sustainable, heavy-duty electrical infrastructure (Hannan et al., 2025).

**Self-Powered Energy Systems**

Anderson et al. (2025) claim that building fully autonomous networks demands simultaneous real-time collection of energy and dedicated accumulation blocks. In other words, to realize self-sustaining operation the system must simultaneously capture surrounding ambient microenergy while performing an immediate storage locally (Li and Wang, 2026). To buffer individual internal modules against fluctuating voltages generated from weather changes or motion the intermediate power management circuit controls electrical current flows (Anderson et al., 2025).

Optimization of integrated blocks may result in development of devices needing no battery changes ever throughout their operational life (Thomas et al., 2024). The integrated block diagram, that covers energy generation and subsequent flow through to application electronics, is shown below (Figure 10).

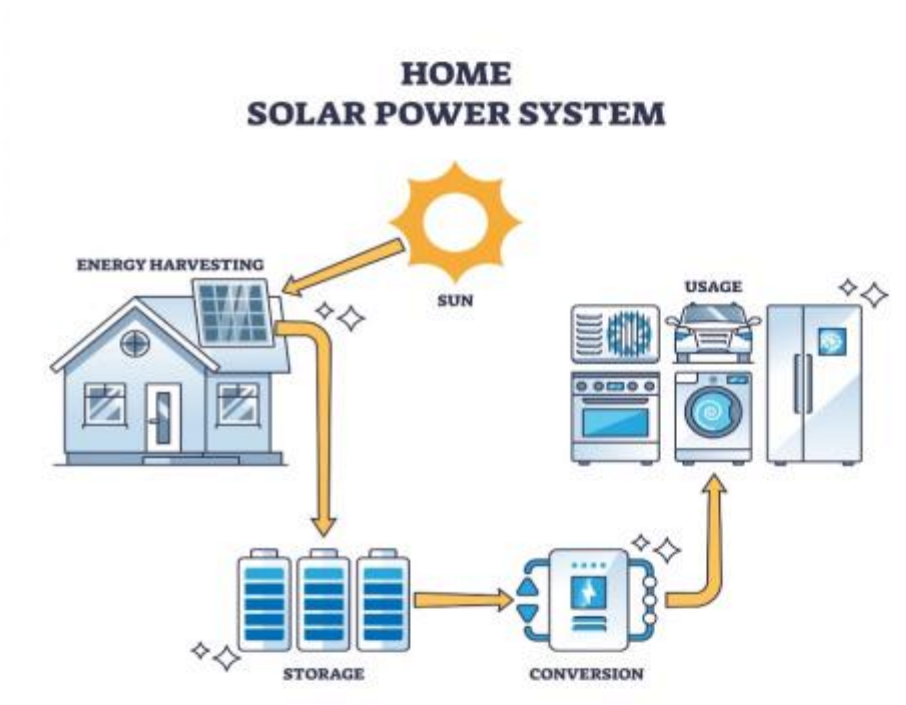


**Figure 10. Integrated self-powered sustainable energy system**
**Source: Anderson et al. (2025)**

Integrated harvesting-storage architectures are increasingly important for autonomous electronics and distributed sensing systems (Thomas et al., 2024). According to Thomas et al. (2024), modern implementations deploy these unified platforms across Internet of Things (IoT) nodes, flexible wearable electronics, and smart environmental sensors. By eliminating heavy power cords and bulky structural battery housings, these compact systems can monitor remote industrial environments and human biometric data completely uninterrupted (Li & Wang, 2026). According to Anderson et al. (2025), using flexible polymer substrates allows the collection and storage units to bend smoothly around structural surfaces and clothing interfaces. Ultimately, these co-designed micro-power matrices provide the foundational infrastructure needed for scalable, maintenance-free distributed computing networks (Thomas et al., 2024).

A comparative breakdown of these integrated system pairings alongside their targeted commercial use cases is detailed below (Table 4).

**Table 3. Integrated harvesting–storage systems and applications**

| System | Harvesting Technology | Storage Technology | Application |
|---|---|---|---|
| **Solar-Capacitor Matrix** | Organic Photovoltaics (PV) (Li & Wang, 2026) | Carbon-based EDLC Supercapacitors (Thomas et al., 2024) | Distributed IoT environmental sensing nodes (Thomas et al., 2024) |
| **Kinetic-Battery Pack** | Wearable Flexible TENG (Anderson et al., 2025) | Thin-film Sodium-Ion Battery (Li & Wang, 2026) | Self-powered health tracking and biometric apparel (Anderson et al., 2025) |
| **Thermal-Storage Node** | Bi-Te Free Thermoelectric Generator (Thomas et al., 2024) | Solid-State Micro-Lithium Cell (Anderson et al., 2025) | Industrial pipe waste heat monitors and alerts (Thomas et al., 2024) |

## Emerging Trends in Sustainable Materials

### Advanced Nanomaterials

The structural identification of low-dimensional nanomaterials revealed altogether new frontiers for designing highly effective energy platforms (Miller et al., 2025). High-conductivity graphene sheets, transition metal carbides (MXenes), functionalized carbon nanotubes and porous metal-organic frameworks (MOFs) have become popular research objects that promote the reaction rate kinetics on the surface, which can facilitate both ion transport and charge polarization thanks to extremely high surface-area-to-volume ratios coupled with tunability of their chemical compositions. All of these phenomena significantly reduce internal resistive losses at the interface of active electrodes when embedded (Park & Choi, 2026). Table 4 below summarizes and compares the primary benefits of these promising eco-friendly nanomaterials.

**Table 4. Emerging sustainable nanomaterials**

| Material | Major Advantage | Current Application |
|---|---|---|
| **Graphene** | Unmatched electron mobility, mechanical strength (Miller et al., 2025) | High-rate conductive current collector backbones (Miller et al., 2025) |
| **MXenes** | Hydrophilic surfaces, metallic conductivity profiles (Park & Choi, 2026) | High-capacity pseudocapacitive aqueous electrodes (Park & Choi, 2026) |
| **Carbon Nanotubes** | Excellent ballistic electron transport paths (Miller et al., 2025) | Flexible conducting nets in wearable electronics (Miller et al., 2025) |
| **Metal-Organic Frameworks** | Ultra-high internal porosity, structural tunability (Park & Choi, 2026) | Targeted ion filtering and host matrices in solid batteries (Park & Choi, 2026) |

### Bio-Inspired and Biodegradable Materials

Sullivan et al. (2024) identified that the incorporation of bio-derived natural materials is an efficient method of removing noxious processing chemicals found in current components. Nowadays the abundant biopolymers such as cellulose nanofibers, delignified lignin, silk fibroin proteins, and marine derived chitosan have gained popularity as components in the next-generation green electronics (Gomez and Fernandez, 2025). Bio-based materials possess diverse surface functional groups allowing easy metal binding, and polymer compounding (Sullivan et al., 2024). Furthermore, this toxic free raw material system also simplifies the waste processing in the end of product life by enabling materials to be naturally degraded as organic materials in terms of composting (Gomez and Fernandez, 2025).

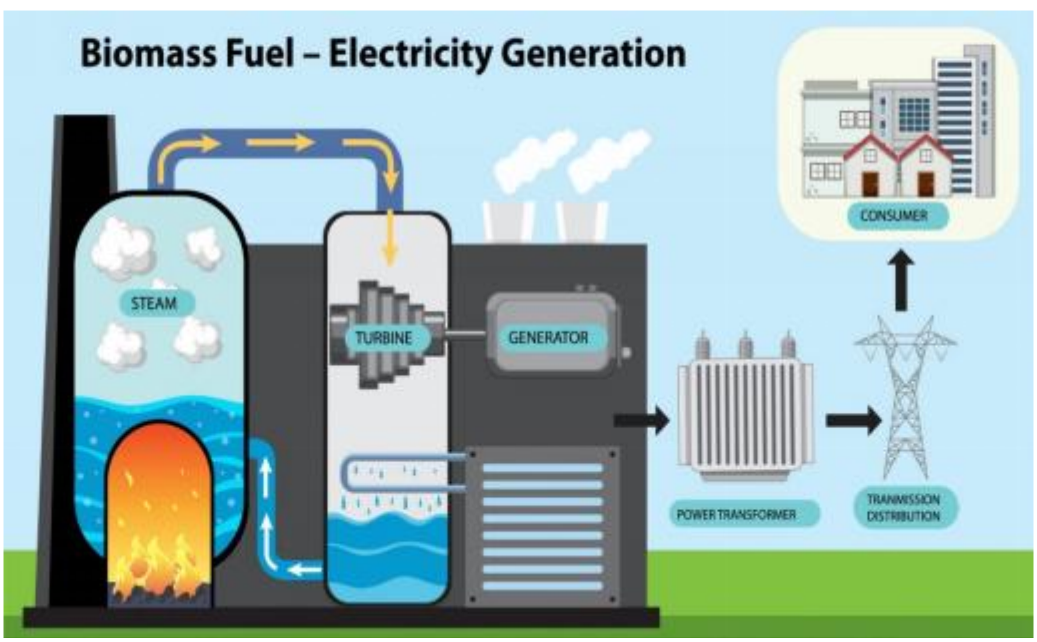


**Figure 11. Bio-based sustainable materials for next-generation energy devices**
**Source: Gomez and Fernandez (2025)**

Transitioning toward these green processing methods allows researchers to establish a truly circular material design framework (Gomez & Fernandez, 2025). According to Gomez and Fernandez (2025), extracting valuable functional polymers directly from agricultural side-streams and forestry waste streams prevents resource competition with food crops. When these bio-based energy devices reach the end of their operational life, their biodegradable substrates can break down without releasing persistent microplastics or heavy metal residues into the environment (Sullivan et al., 2024). According to Miller et al. (2025), this circular loop transforms electronic devices from traditional single-use products into fully degradable organic assemblies. Consequently, optimizing these renewable feedstocks directly mitigates electronic waste accumulation while supporting global carbon reduction targets (Sullivan et al., 2024).

### Artificial Intelligence and Materials Discovery

Machine learning methods have already reduced the timeline for historical functional energy material component design from several years to weeks (Ibrahim et al., 2025). Current computer design processes employ high-capacity neural networks, capable of assessing many hundreds of hypothetical crystal structures or chemistry compositions in parallel (Ibrahim et al., 2025). The resulting computational prediction of properties such as ion diffusion kinetics and band gaps layout makes it possible to rapidly discover best configuration before a physical wet-lab measurement is required (Mller & Fischer, 2026), therefore reducing experimental time significantly, compared to a typical trial-and-error based experimental laboratory design.

Machine learning algorithms can automatically mine underlying correlations from crystal structure features to final device efficiencies, replacing the reliance of current methods on limited raw materials with eco-friendly and low-cost components (Ibrahim et al., 2025), as well as tailoring synthesis conditions in order to reduce energy consumption in production (Mller & Fischer, 2026).

## Challenges and Future Perspectives

### Current Challenges

The translation of sustainable materials from laboratory research into viable products demands that manufacturers overcome multiple large-scale production bottlenecks, Davidson et al. (2025). At the technical level, the challenges for large-scale adoption revolve around the inability to effectively and affordably scale many technologies, the lack of long-term structural durability during repeated stresses, and costly production (Patel & Kumar, 2026). For example, bio-based polymers offer promising rates of biodegradability, yet many degrade quickly outdoors and undergo accelerated loss of strength when operated repeatedly (Davidson et al., 2025). The inability to achieve reproducible batch manufacturing practices is linked to variability in input raw materials such as biomass (Patel & Kumar, 2026). Table 5 outlines specific manufacturing challenges and their corresponding engineering solutions.

**Table 5. Challenges and potential solutions**

| Challenge | Impact | Possible Solution |
|---|---|---|
| **Scalability Constraints** | Industrial production lags due to complex nanomaterial synthesis steps (Patel & Kumar, 2026) | Develop continuous roll-to-roll chemical deposition systems (Patel & Kumar, 2026) |
| **Long-Term Performance Loss** | Natural polymers degrade rapidly under moisture and heat cycles (Davidson et al., 2025) | Implement non-toxic cross-linking agents and green protective sealants (Davidson et al., 2025) |
| **High Initial Costs** | Advanced materials struggle to compete with cheap fossil fuel components (Patel & Kumar, 2026) | Utilize low-cost agricultural side-streams as raw precursors (Patel & Kumar, 2026) |

### Future Research Opportunities

The next evolution in materials engineering as seen by Carter et al. (2025) to feature a significant expansion in designing multi-functional material systems in a synergistic combination of several energy-based features. New research programs must focus on using non-toxic solvents green synthesis techniques, coupled with water-based processing to complete the circular economy (Nguyen & Morrison, 2026). By integrating smart materials and hybrid energy systems, future systems may tune their output based on environmental conditions in response to hybrid smart materials (Nguyen & Morrison, 2026).

The combination of disciplines from chemistry and materials science to mechanical engineering and data science - allows researchers to rapidly overcome complex integration issues (Carter et al., 2025). In the process, such integrated research can quickly optimize materials for mechanical stresses and scale from the get-go (Nguyen & Morrison, 2026). Industrial alignment is crucial: The research community is now working toward connecting new findings directly with commercial production processes (Patel & Kumar, 2026).

## Conclusion

The present extensive review summarizes and elaborates on the tremendous progress of emerging sustainable materials in energy harvesting and storage fields. Intensified threat of global energy crisis and compelling global climate warming imperatives demand a revolutionary shift from the established toxic and resource-limited materials towards earth-abundant and environment-friendly substitutes. Researchers classify those materials based on different compositions and structure from naturally derived matrices of cellulose to advanced materials, for instance, low-dimensional systems such as MXenes and graphene, demonstrating the impact of controlling the atomic structures to dictate the macroscopic device performance and cyclic stability.

For the future, a few important obstacles need to be overcome, such as large-scale production limitations, environment moisture degradation, and cost-efficiency for materials development from fundamental understanding to commercial application. Trends like ML-enabled predictions for accelerated property and a comprehensive roadmap based on circular bio-inspired design parameters to addressing challenges related to long term stability and cost-effectiveness. For that, the key strategy will be to bridge chemistry and device engineering through the cross-cutting efforts from different disciplines. Commercialization opportunities arising from sustainable materials will speed up the advancement of clean technology.

### Authors' Contributions

The authors of this research have significantly contributed to the study's conception, data collection, and manuscript development. All authors were involved in writing the manuscript or critically reviewing it for its intellectual value. They have reviewed and approved the final version for submission and publication and accept full responsibility for the content and integrity of the work.

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