Transient, Biodegradable Energy Systems as a Promising Power Solution for Ecofriendly and Implantable Electronics

Kaveti Rajaram, Seung Min Yang, and Suk-Won Hwang*

Along with the rapid growth in electronics technology, electrical power solutions are developed to provide high-performance, reliable, and durable energy supplies to various electronic devices. However, conventional power systems are challenging owing to serious after-use considerations, including environmental costs and biological hazards of eliminating heavy metals and other toxins. Here, this Perspective provides a comprehensive review of recent progress in techniques associated with transient, biodegradable, environment-friendly energy solutions, including batteries, supercapacitors, energy harvesters utilizing various types of energy sources (e.g., biochemical, physical/mechanical, or thermal), and external energy transfer strategies (e.g., inductive coupling/radiofrequency, photovoltaic, or ultrasonic). Key features, practical examples, existing challenges, and finally possible future directions for transient, biodegradable energy solutions with unmet approaches yet are presented.

1. Introduction

While the developments of conventional electronics highlight robust, consistent, and long-lasting operation, advances in the other class of electronics encourage the contrary, where they can completely disintegrate, decompose, degrade, or disappear in a well-regulated way, after a desired lifetime. This technology, referred to as transient or biodegradable electronics in a broad sense, has been made for a variety of applications, typically, environmental monitors, hardware security electronics, biomedical sensors, has been made for a variety of applications, typically, environmental monitors, hardware security electronics, biomedical environmental monitors, hardware security electronics, biomedical

ims/sensors/stimulators, and bioelectronic medicines or drug delivery systems.[1–3] Previous reports have established dissolution chemistries of constituent materials, including semiconductors, metals, dielectrics, substrates, and polymeric composites, along with studies of mechanical softness and deformability of electronic components.[4–10] Despite such significant developments in this research realm, power solutions to biodegradable electronic systems remain challenges. Predominant energy source techniques, represented by lithium-ion batteries, have faced a rise of environmental concerns and complications that must be eliminated or replaced when used in biomedical applications.[11–13] Toxins produced after disposing batteries include heavy metals, such as cobalt, nickel, cadmium, etc., that pose adverse effects on environment and health, motivating to develop biologically benign materials for ecofriendly energy storage systems. In the clinical case of delivering power to a bioresorbable implant with an externally wired source, the electric wires passing through the skin and tissues may corrode and disconnect, or pathogens could enter the surgical area, which may cause secondary infection.[14,15] Depending on the location or purpose of the device, the surgical procedure for connecting the external power source is complicated and sometimes impossible, requiring fully implantable formats that include bioresorbable power solutions.[16] In this context, recent studies suggested various strategies for transient, biodegradable energy devices and systems that not only provide a continuous and reliable power supply to other electrical devices but also reduce environmental costs and biological risks at the end of the supply duty.

Figure 1 illustrates systems categorized with energy supplying methods, including 1) self-sustaining energy storage devices, for instance, battery and supercapacitor, that typically consist of one or merged electrochemical cells generating electrical power;[17–20] 2) self-powering systems that collect electricity via converting other types of waste energy, such as physical/mechanical (triboelectric, piezoelectric) or chemical (galvanic) species;[21–24] 3) energy transmission systems that can deliver power without wired connections, via radiofrequency (RF) electromagnetic fields and light illumination;[25–30]; and 4) envisioned energy sources for future directions, including thermoelastic, bioelectronic (biofuel, biopotential) sources, and ultrasonic waves. Each system operates with different mechanisms and timescales, requiring consideration of proper material selections, device structures, and integration...
strategies. We begin with reviewing of recent progress in technologies related to transient, biodegradable energy solutions as well as key features and practical uses with representative examples. Finally, the conclusion summarizes current challenges and suggests future directions with unexplored research paths yet.

2. Energy Storage Systems

Batteries and supercapacitors have made tremendous progress in performance over the past two decades, while sustainability, environmental effect, as well as a life cycle and safety issue have been relatively neglected. As explosive demand for energy systems in electric vehicles is expected to produce a large volume of wastes that contain toxic components, reformulation of device structures and associated technologies with environmentally benign materials and chemistries is essential for a green or sustainable energy future.\(^{[42-46]}\) In this section, we discuss emerging biodegradable battery and supercapacitor systems, including approaches such as injectable, rechargeable batteries, 3D-printed disposable supercapacitors, and their sustainable chemistries, materials, and degradation manners.

2.1. Batteries

Figure 2a shows materials and device configurations to fabricate a sodium-ion secondary battery consisting of sodium- and iron-based polyanion compounds and pyroprotein-based carbon with cellulose-derived binders as composite electrodes, a porous cellulose acetate mesh as a separator, sodium perchlorate in a propylene carbonate solution as an electrolyte, and carboxymethyl cellulose/polyester/silicon-based materials as a biodegradable encapsulation pouch.\(^{[47]}\) The assembled battery exhibited comparable electrochemical performances as those of conventional non-degradable ones, with a charge-discharge capacity of 110 mAh g\(^{-1}\) and cycle retention of 93%. The natural biodegradation of battery begins when the pouch was contacted with water/moisture/fungi in the soil and it dissociated into silicic acid, glucose, terephthalate, adipate, and 1,4-butanediol via natural microbial degradation and hydrolysis reactions. The cathode was hydrolyzed into sodium, iron, phosphate, and pyrophosphate; the binder and cellulose separator were transformed into glucose via fungal degradation; and the electrolyte was degraded into ethanol, methanol, carbon dioxide, propylene glycol, sodium, and chloride via natural hydrolysis and microbial degradation. Cytotoxicity tests revealed that all the components of the battery were naturally biodegraded without any toxic end products. Figure 2b presents a highly flexible, rechargeable aqueous fiber battery that could be directly injected into the body with minimal invasion.\(^{[48]}\) A particular design strategy of the conductive fiber of polyglycolic acid (PGA) yarn was to utilize incorporation with polydopamine/polypyrrole as an anode, MnO\(_2\) as cathode, chitosan as a separator, and body fluids for an electrolyte. The anode and cathode were twisted together to accomplish a fiber battery, which exhibited high flexibility by
Figure 2. Energy storage systems. a) Overall description of materials and structure of an ecofriendly, water-soluble sodium-ion secondary battery (left), an optical image of the device, and compostable decomposition in the plant on day 120 after burial (right). Reproduced with permission. [47] Copyright 2021, Wiley-VCH. b) Fabrication and implantation process of biodegradable, injectable, and rechargeable fiber battery (left), a set of dissolution images of an assembled fiber battery during dissolution in phosphate-buffered saline (1×) at 37 °C, with a magnified view of the device in the inset (right). Reproduced with permission. [48] Copyright 2021, Royal Society of Chemistry. c) Schematic of a degradable, metal-free polypeptide-based organic radical battery and corresponding reactions that occur during charging and discharging. Reproduced with permission. [49] Copyright 2021, Springer Nature. d) Exploded view structure of a fully biodegradable magnesium–molybdenum trioxide (Mg–MoO₃) battery (left), and optical images of degradation behaviors in phosphate-buffered saline (pH 7.4, 37 °C) (right) solution. Reproduced with permission. [50] Copyright 2018, Wiley-VCH. e) Illustration of a fully 3D-printed degradable paper supercapacitor, an assembly approach (left), and optical images collected at different time stages during disintegration of supercapacitors under simulated aerobic composting conditions (buried in soil at 58 °C for 63 d) (right). Reproduced with permission. [52] Copyright 2021, Wiley-VCH. f) Fabrication process of all-printed, nature-friendly green micro-supercapacitor (left), and a couple of dissolution images in distilled water observed for a short timescale within a minute (right). Reproduced with permission. [53] Copyright 2021, American Association for the Advancement of Science. g) A fully biodegradable planar type of supercapacitor with a configuration of dissolvable metals/NaCl/agarose gel electrolyte (left), and dissolution images of Mo-interdigitated electrodes in phosphate-buffered saline (pH 7.4) at 37 °C (right). Reproduced with permission. [54] Copyright 2017, Wiley-VCH.
maintaining 89% of capacity even after 1000 cyclic tests at a bending angle of 180°. In vivo injection of fiber batteries into the abdominal subcutis of a mouse model demonstrated a specific capacity of 25.6 mAh g⁻¹ at a current density of 1000 mA g⁻¹ with a retention of 69% after 200 charge/discharge cycles. The implanted battery system gradually dissolved upon hydrolysis, enzymolysis, and completely disappeared after 10 weeks without the need of surgical interventions. Potential alternative, metal-free, all-polypeptide organic-based redox-active amino acid materials were developed to fabricate a sustainable, rechargeable, and on-demand degradable battery, as illustrated in Figure 2c.[49] Redox-active polypeptides and small-molecule peptide repeated units were synthesized to verify redox potentials and identify degradation products. A composite of metal-free, polypeptide-based cells incorporated with viologen-chloride polypeptide was used as an anode, biTEMPO (2,2,6,6-tetramethyl-4-piperidine-1-oxyl) polypeptide composite was used as a cathode, and electrolyte-soaked filter paper served as a separator, for a polypeptide-based battery. The resulting performance indicated a fair electrochemical performance and stable operation with a maximum charge capacity of 37.8 mAh g⁻¹ and cycling stability of 250 cycles at 1 C (the current required to reach full charge in 1 h). The viologen and biTEMPO polypeptides are constructed such that it comprises amide links in the backbone and easter links in the side chains, that are prone to degradation in enzymatic, basic, and acidic environments; therefore, on successive on-demand degradation in acidic conditions (1 and 6 M hydrochloric acid (HCL) at 80, and 110 °C), both polypeptides generated L-glutamic acid and n-hexylamine. Cell viability study revealed that the degradation products showed lower toxicity effects on mouse fibroblast cells and bovine coronary venular endothelial (CVE) cells. Primary batteries with completely dissolvable materials could play an essential role in powering temporary electronic implants for the prevention, treatment, and management of illness. Figure 2d presents materials and device configuration of a fully biodegradable magnesium–molybdenum trioxide (Mg–MoO₃) primary battery, wherein Mg and MoO₃/Mo served as anode and cathode materials, respectively; sodium alginate with phosphates was used as an electrolyte.[50] A single-cell Mg–MoO₃ battery showed high electrochemical performance with a stable output voltage of 1.6 V, capacity of 6.5 mWh cm⁻², and output current of 12.5–150 μA cm⁻², for an extended lifetime of up to 13 days, and demonstrated operational functionality by powering a light-emitting diode (LED), calculator, and amplifier of an electrocardiogram (ECG) signal detector. As Mg serves with excellent biocompatibility/biodegradability (daily allowance: ≈300 mg d⁻¹) and with high solubility of MoO₃ in aqueous solutions (≈1 g L⁻¹), the fabricated battery completely dissolved within 9 d in PBS (pH 7.4) at 85 °C. Implanted batteries into the subdermal region of rats completely disappeared after 4 weeks without overt cell reactions and thus validated the possibility for potential on-board advanced power sources. Hydrogel-reinforced cellulose paper-based Zn paper batteries were developed by simple screen printing of Zn microparticles-composed anode ink and Ni- or Mn-composed cathode ink on the front and back of the paper, respectively. The flexible battery showed an areal capacity of 1.1 mAh cm⁻², an output voltage of 1.7 V for a single unit, 500 charge discharge⁻¹ cycles, and it powered a mini electric fan for 45 min continuously. The hydrogel-reinforced cellulose paper became fractured after 2 weeks of burial in natural soil and completely degraded in 4 weeks.[51]

### 2.2. Supercapacitors

Supercapacitors can be considered as an important alternative to electrochemical energy storage option, as they have high power density, fast charge/discharge rates, and lower complexity compared with batteries.[55–57] Figure 2e illustrates a disposable supercapacitor (electrical double layer capacitor, EDLC) with a configuration of two half cells folded into one working device, by a direct ink writing procedure.[52] Various viscoelastic water-based inks with shear-thinning and yielding behaviors were prepared using nontoxic and renewable materials.[58–60]; 1) nanocellulose as a rheological modifier, dispersing, and gelating agent; 2) graphite flakes and carbon-black particles dispersed in shellac for a current collector ink; and 3) carbon, graphite, nanocellulose, and water composite as electrode ink and glycerol/NaCl–nanocellulose composite as electrolytic ink. Fully printed, disposable paper supercapacitors exhibited an absolute capacitance of 61.1 mF at 1 mV s⁻¹, volumetric capacitance of 135 mF cm⁻³, a working voltage of 1.2 V, and excellent mechanical properties with reliable cyclic behaviors. As the supercapacitor is fabricated exclusively with disposable materials, after completing its operation, the system was put in a protective mesh and completely buried in soil (at 58 °C) composed of sawdust, rabbit feed, sugar, corn starch, urea, and compost. The system disintegrated and lost 50% of the original mass in 9 weeks, thus demonstrating a potential strategy toward manufacturing sustainable energy devices. Miniaturized energy storage devices with cost-effectiveness, green processability, and scalable manufacturing capability are crucial for reducing burdens on environmental issues. Figure 2f describes an all-printed and flexible supercapacitor, based on highly porous nanostructured carbon films as an electrode and naturally derived 2-hydroxyethyl cellulose constituting ionic liquid choline lactate as an ionogel electrolyte.[53] Ultrathin geometry (thickness, <10 μm) allows the supercapacitor system to reliably operate against external mechanical deformations, which did not affect electrical performance, as can be seen from a maximum power value of 2.4 mW cm⁻² and stored energy of 0.36 μWh cm⁻². The lightweight, all-naturally derived supercapacitor rapidly disintegrated within a minute and completely dissolved after a day in aqueous and physiological media without any visible traces. Similar types, yet inorganic materials-based supercapacitors in an implantable form are presented in Figure 2g.[29] 2D, in situ-grown defective amorphous MoO₃ flakes on Mo foils via one-step electrochemical oxidation (electrodes), and sodium alginate gels (electrolytes) produced robust, high-performance supercapacitors that reached a high areal capacity of 112.5 mF cm⁻² at 1 mA cm⁻², an energy density of 15.64 μWh cm⁻², and a high-power density of 2.53 mW cm⁻². In vivo examinations on implanted supercapacitors in the dorsal side of rat models demonstrated electrical operations via powering red LEDs after charging and complete dissolution in 6 months through a series of metabolic and hydrolytic reactions without any inflammatory responses. Figure 2h shows a simple planar-type microsupercapacitor that involves dissolvable metals.
(W, Mo, and Fe) as electrodes as well as current collectors and a biodegradable NaCl/agarose hydrogel as an electrolyte.\textsuperscript{[54]} The resulting supercapacitors obtained a highest areal capacitance of 1.6 mF cm\textsuperscript{-2} at a current density of 0.15 mA cm\textsuperscript{-2}, and power density of 1.0 mW cm\textsuperscript{-2} at an energy density of 0.0083 μWh cm\textsuperscript{-2}, which are comparable with those nontransient supercapacitors. Dissolution tests were performed using interdigitated Mo electrodes in PBS (pH 7.4) at 37 °C, and faint color change and complete degradation occurred after 3 days and 9 days through hydrolysis in the form of oxide or hydroxide, while capacitances as a functional operation decreased to half of the initial value after 6 h. A direct fabrication of arbitrary conductive graphene micropatterns on naturally fallen leaves using ultrashort laser pulses was developed. The localized laser heating of leaf induced the transformation of organic compounds to an amorphous carbon material and then facilitated the formation of efficient graphene. The laser induced graphene microelectrodes on leaves showed a sheet resistance of 23.3 Ω Sq\textsuperscript{-1}. To demonstrate the potential application of this technique, a flexible micro-supercapacitor was fabricated. The supercapacitor exhibited an areal capacitance of 34.68 mF cm\textsuperscript{-2} at 5 mV s\textsuperscript{-1}, capacitance retention of 99% after 50 000 charge-discharge cycles, and it can power an LED or a table clock.\textsuperscript{[63]}

The development of transient, biodegradable energy storage devices with improved volumetric energy density is essential for higher energy storage to extend the operational time of the devices and improving their safety is the fundamental criteria for biomedical electronic devices.\textsuperscript{[64–66]} Although fabrication of very thin metal electrodes could increase the surface area and output power of the energy storage devices, the redox reaction and degradation rate of the metal electrodes also increase. Therefore, the device design must be optimized to retain the amount of metal dissolved in the body within the maximum daily allowance. The toxicity issues that arise from the leakage of organic electrolytes of energy storage devices could be avoided using body fluids such as sweat or sweat equivalent solutions, urine, saliva, gastric fluids, or blood as electrolytes in transient, biodegradable energy storage devices and could offer considerable progress.\textsuperscript{[67–70]}

3. Self-Powering Systems

Considering the volume and structure limitation by electrolytes of electrochemical energy storage devices in the previous chapter, self-powering systems can be alternative power sources with advantages of soft, miniaturized, and self-sustained forms. Recent studies realized dissolvable materials-based implantable triboelectric devices that convert biomechanical energies into electrical outputs for self-powered therapies.\textsuperscript{[71–75]}

Figure 3a

\begin{figure}[h]
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\caption{Examples of fully biodegradable, implantable self-powering systems. a) Overall information on materials and structures of a degradable TENG using microstructured poly(lactic-co-glycolic acid) (PLGA) (left), sequential images of their degradation and working principle (middle), and bone healing performances in biological models (right). Reproduced with permission.\textsuperscript{[14]} Copyright 2021, National Academy of Sciences. b) Biodegradable poly(L-lactic acid (PLLA)-based piezoelectric nanofibers that convert vital physiological pressures to electrical outputs and generate acoustic pressure to release drugs by electrical inputs (left); a set of photographs indicating dissolution studies in buffered solution and in vivo implantation (right). Reproduced with permission.\textsuperscript{[81]} Copyright 2020, National Academy of Sciences. c) Dissolvable and self-electrified conduit device for in vivo nerve regeneration through structural guidance and electrical cues. Magnesium anode and iron–manganese alloy cathode on each side of the conduit compose a galvanic cell that can provide sustained electric fields across body fluids as an electrolyte. Reproduced with permission.\textsuperscript{[35]} Copyright 2020, American Association for the Advancement of Science.}
\end{figure}
shows a triboelectrically self-powered and bioresorbable electrostimulator for accelerating recovery of bone fractures.[13] The triboelectric generators consisted of Mg electrodes and poly (lactic-co-glycolic acid) (PLGA)-based pyramidal microstructure arrays. Particularly, pyramid-shaped micropatterns on the triboelectric surfaces could improve contact area and increase the effective dielectric constant by the presence of air voids, which caused large capacitance changes during deformations, thus providing sufficient electric pulses. Repetitive vertical contacts separations between the PLGA micropyramids and electrodes generated continuous pulsed outputs, which stimulated endogenous electric fields to modulate bioelectric states and accelerated fractures healing. Compared with conventional stimulators for postoperative treatments, the triboelectric systems could be attached to irregular tissue surfaces to generate stable electrical pulses of 4.5 V over 6 weeks, in a fully implantable and flexible manner without external power sources. After complete operations, the implanted devices were gradually resorbed in the biological environment, which eliminated the process of invasive surgical removal. These triboelectric devices are promising tools for supplying electricity to biointegrated devices implanted in sites with repetitive mechanical movements, such as beating cardiac tissues, vibrating vocal cords, bending diaphragms, or pulsing blood vessels.[76–80] Similar to triboelectric generators, piezoelectric devices generate electrical power under mechanical motions via conversion of applied mechanical stress. Figure 3b shows an example of a biodegradable piezoelectric system that utilized poly(L-lactic acid) (PLLA) nanofibers and molybdenum (Mo) electrodes to transduce electrical signals and mechanical movements in the brain.[81] The reversible operation of the devices in the rat brains could not only monitor changes in intracranial pressure (ICP) via generated electricity but also open the blood–brain barrier with the induced vibrations by external electrical inputs. The pressure generated linear voltage output in both flat and stretching states as well as provided stable output of over 2 V after 10 000 cycles at applied 10 N force. The flexible nature of the device produced larger deformations, resulting in much higher piezoelectric performance than the early reported biodegradable piezoelectric devices,[13] and improvement of crystallinity and orientation of polymer chains could increase the piezoelectric response.[82,83] Following the histology analysis with device implantations in rat craniotomy defects, the PLLA degraded within 4 weeks and the molybdenum electrodes degraded for a longer time, while similar devices could maintain functional outputs until 8 days in physiological conditions (PBS, 37 °C). The self-electrified conduit device in Figure 3c provides another strategy that sustains continuous electric energy without any external power sources.[15] Porous polycaprolactone (PCL) conduits guided the growth of nerve fibers during the healing process of transected peripheral nerves, while magnesium (Mg, anode) and iron–manganese alloy (FeMn, cathode) at each end of the conduits worked as a galvanic cell between biofluid electrolytes, generating electricity to aid recovery. The electroactive devices could provide sustained potentials to induce continuous electrostimulations during the postoperative period, promoting peripheral nerve regeneration. When operating with body fluid as an electrolyte, average open-circuit voltages (OCVs) of 0.984 on day 1, 0.450 on day 2, and then 0.068 V on day 3 were observed, due to degradation of Mg electrodes. The lifespan of the devices could be extended by increasing the thickness of electrodes or improving encapsulation layers.[16] These miniaturized biodegradable galvanic cells may be applied to a variety of damaged tissues and organs to enhance their healing process, as well as where it is necessary to supply power with a constant voltage using body fluids as electrolytes.

4. Energy Transfer Systems

Along with the aforementioned self-sustained power strategies, external energy that can pass through tissues can supply reliable power to implanted bioelectronic devices. Photovoltaic (PV) devices operating at near-infrared (NIR) wavelengths can be an effective option for wireless energy transfer.[84,85] Figure 4a shows fully biodegradable PV devices that were composed of amorphous silicon-based PIN diodes and Mo electrodes.[19] The PV arrays generated 242 μW under direct illumination, 96.4 μW under illumination through the skin, and 64.4 μW under illumination through the skin with fat, while output voltages were 5.23, 4.64, and 4.25 V for each condition, respectively. Increasing the thickness of active Si films may improve PV performance; however it is necessary to consider the solubility in the body. To demonstrate their function as a bioresorbable power source, PV devices were implanted in the rat brain and subjected to NIR illumination to generate electrical power. The implanted systems provided reliable power to a connected LED until the third day after surgery. In the following period, Mo electrodes first disappeared within nine days and complete dissolution and bioresorption of the remaining Si PV array was confirmed via histological assay after 4 months. Low-intensity NIR light in this demonstration was comparable with the low level used for muscle repair and pain relief in conventional clinical settings, thus, illustrating a possible energy solution for implantable biointegrated electronic systems. Developments of PV materials and cells that could power wearable/epidermal and implantable electronics by directly harvesting energy from emitted thermal radiation from the surface of the human body, by accessing the readily available direct sunlight, could open doors for various envisioned transient, biodegradable energy transfer systems.[40,86] Besides IR radiation, resonant inductive couplings can wirelessly transmit electrical power to other systems. Figure 4b illustrates a fully bioresorbable cardiac pacemaker using a wireless inductive coil for a battery-free power supply.[40] The wireless system included an RF dual-coil antenna and a silicon nanomembrane (Si NM)-based p–n diode that rectifies alternating voltage and improves power transfer efficiency. The sinusoidal (alternating current, AC) input of 7 peak-to-peak voltage (Vpp) from a transmitter coil (1 mm away) induced almost direct current (DC) output of 13.2 V at contact pads, where magnetic coupling occurred at the megahertz frequency domain (13.5 MHz), avoiding absorption by biofluids or tissues. The output voltage was proportional to the magnitude of the input voltage and decreased as the distance between transmitter and receiver coils increased. Temporal device implants mostly disintegrated and dissolved within 5 weeks, and remaining debris completely disappeared after 7 weeks during immersion in PBS solution at the physiological conditions (pH 7.4, 37 °C). In vivo pacing tests in canine models that have cardiovascular
systems with highly relevant scale and physiology with those of humans demonstrated that the implanted wireless devices could deliver electrical stimuli at an intended rate and frequency with a skin-to-transmitter distance of 10 cm, for epicardial pacing in large animals. Subsequent in vivo results using rat models illustrated successful operation in which wireless stimuli changed ECG signals from a narrow and consistent sinus rhythm (350–400 bpm) to a widened, amplified rhythm (400–450 bpm) until postoperative day 4; then, the transfer efficiency decreased at day 5 and failed to pace at day 6. Most part of the device dissolved after 4 weeks, and the remaining material residues completely disappeared after 12 weeks. A transient ultrasound-mediated triboelectric nanogenerator (TENG) capable of ultrasound-triggered energy generation as well as degradation was developed using Mg electrode (100 nm thick), a porous poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) membrane (50 μm thick), and a polyethylene glycol-based polymeric composite (PHBV/PEG (7:1)) layer (50 μm thick). The fabricated device generated a stable electrical output of 4.61 V and 27.8 μA under low ultrasound intensity (0.5 W cm⁻²), while higher ultrasound intensity (≥3.0 W cm⁻²) initiated the material degradation due to the locally intensified acoustic pressure resulting from porosity. The ex vivo evaluation of the device in a porcine tissue revealed that the device stopped generating electric power when exposed to an ultrasound intensity of 3.0 W cm⁻² for 20 min and thus, demonstrated a promising hybrid technology for powering transient, biodegradable electronic devices/systems.

5. Envisioned Energy Systems for Future Directions and Challenges

Significant advancements were achieved in the field of transient, biodegradable energy devices that can deliver power to various active devices, as discussed in the previous sections. Further exploration and development of more versatile and advanced energy storage, harvesting, or supplying systems that could be transformed into a transient, biodegradable form are indispensable to broaden the potential applications of dissolvable energy systems. In this section, we discussed possible future directions and challenges ahead in transforming or adapting some of the nondegradable counterpart technologies, including wood-based heat-to-electricity conversion, biopotential energy harvesting, and ultrasonic energy transfer.

Figure 5a presents an approach of a chemically transient lithium-ion rechargeable battery that has stable battery performance with high voltage as well as high capacity and can be fully dissolved in water within minutes due to triggered cascade reactions. The transient rechargeable battery is composed of lithium (Li) metal foil as an anode, vanadium oxide (V₂O₅) as a cathode, polyvinylpyrrolidone (PVP) nanofiber membrane as a separator, aluminum (Al), copper (Cu) as a current collector, and sodium alginate (Na–AG) as an encasement. Adding a few water droplets to the Li–V₂O₅ battery resulted in complete disintegration and fast disappearance through a series of reactions in a specific manner. First, Na–AG dissolved and then the PVP membrane separator dissolved in water, which generated hydrogen.
gas, LiOH, and heat due to the rapid reaction of water with Li metal. The resulting alkaline solution rapidly reacted with V_2O_5 as well as Al current collector, resulting in complete dissolution of the battery within a minute. The Li–V_2O_5 transient battery showed an output voltage of 2.8 V, deliverable energy of 0.29 mWh, and a single-cell energy density of 480 Wh kg⁻¹ as well as stable charge-discharge curves with a maximum discharge capacity of 136.5 mAh g⁻¹. Although this work demonstrates the first transient secondary/rechargeable battery inspired by Li-ion battery technology, the application of this device in biomedical and ecofriendly electronics is severely limited due to the generation of alkaline solutions that can cause adverse biological and ecological effects. Therefore, alternative approaches such as using green energy storage materials derived from redox-active biopolymers with controlled degradation capabilities could be developed. Further investigations on expanding the material toolbox beyond classical battery materials, structures, and toxicity of questionable components or end products are essential to apply these strategies and develop various envisioned transient, biodegradable energy storage systems. Generating electricity from low-grade heat offers a wide range of potential applications involving temperature sensing and thermal energy harvesting. Figure 5b presents chemical treatment of natural wood to produce a naturally aligned flexible, lightweight, and biocompatible cellulose nanofiber membrane with a negatively charged surface. NaOH-based polymer electrolyte was infiltrated into the cellulose membrane and upon applying an axial thermal gradient resulted in a significant enhancement in thermally generated voltage of 24 mV K⁻¹ due to selective impregnation of Na⁺ ions and repulsion of OH⁻ ions in the NaOH solution by the cellulose membrane. The electrolyte-infiltrated cellulose membrane was charged to 0.118 V with a response time of 70 s, and discharged in 170 s, at 500 nA cm⁻². This work demonstrated a sustainable and cost-effective solution for low-grade thermal energy harvesting; however, replacing the cellulose membrane with reliable biodegradable polymeric ion species with higher surface charge could be used in biomedical applications. Furthermore, the study of biodegradation, lifetime, long-term stability, and optimization of electrodes for continuous operation of these heat harvesting systems could provide enhanced, large-scale energy harvesters for envisioned research areas in transient electronics. Figure 5c illustrates the structure and mechanism of the eel’s electric organ and the implementation of an artificial electric organ prototype from biocompatible materials. Four compositions of hydrogel tetrameric repeating units, namely, a high-salinity hydrogel, a cation-selective gel, a low-salinity gel, and an anion-selective gel, were in sequence formed for ionically conductive pathways, leading to electrolyte gradients across tens of thousands of selectively permeable compartments. Resulting devices generated an open-circuit voltage of 110 V and power densities of 27 mW m⁻² per tetrameric gel cell upon simultaneous, mechanical contact activation. Further, a trilayered electrically active contact lens was developed to generate a potential difference of 80 mV, using these hydrogel films. The artificial electric organ presented the possibility of developing a bioinspired, deformable, and biocompatible electric power source, while the output power of biochemical harvesters was limited to the redox potentials of oxygen and biomolecular fuels. Therefore, further developments in advanced design strategies such as connection of multiple biofuel cells in series could improve output power capacity. Ultrasonic energy transfer is attracting much attention due to advantages...
including low attenuation in biological tissues, good special resolution, and high safety at low power. Figure 5d presents a capacitive-type ultrasound energy harvester that creates power via vibration of a thin, implantable triboelectric generator.\(^{[93]}\) The system consists of a perfluoralkoxy vibrating polymer membrane (thickness: 50 μm) as a triboelectric layer that was suspended (air gap: 80 μm) on a thin copper electrode, whose ultrasound-induced displacements in the polymer membrane generated maximum output power of 6.74 mW and a current of 450 μA. Such components could charge a 4.7 mF capacitor and 700 μA h Li-ion battery in 4.5 h. Furthermore, ex vivo demonstration of the vibrating ultrasonic energy harvester in porcine skin generated an output voltage and current of 2.4 V and 156 μA at 5 mm depth, and 1.93 V and 98.6 μA at 10 mm depth, sufficient to recharge batteries and small implants. However, issues such as scattering, absorption, and coupling of acoustic signals at the tissue interface need to be resolved to increase the efficiency of ultrasound energy. Furthermore, the presented ultrasound energy harvester prototype consists of various nonbiodegradable materials, and they can give rise to various medical issues in the long term in vivo. Therefore, as an alternative, a fully biodegradable ultrasound energy harvester could be developed by adopting the present prototype but using transient, biodegradable high-performance piezo-/triboelectric polymers, biodegradable metals, and novel structural strategies for realizing high-performance transient, biodegradable ultrasound energy harvesters.\(^{[20,97]}\)

6. Conclusion and Outlook

Only a certain class of transient, biodegradable energy harvesting systems have reached the output power of mW level; other systems are still in the range of nW to μW. Such limited power capacity produced through particular energy harvesters (TENG, piezoelectric, thermoelectric and biopotential/biofuel harvesters) from diverse resources may not be considered as ultimate solution providers; however, these systems are still useful for small-sized or short-term electronic implants. Transient, biodegradable, rechargeable electrochemical energy storage devices with better packaging designs could provide a key solution to power active systems over extended periods even in the absence of any external power sources. Bioresorbable batteries can provide high energy density and could be deployed easily at any locations of target organs for long-term power supply. Supercapacitors offer higher power density, fast charge/discharge rates, and multiple tiny supercapacitors connected in series that could provide larger outputs for short-term power needs. External delivery of power through inductive coupling, RF electromagnetic fields, light illumination, or ultrasonic waves allows for devices with miniaturized form factors, lightweight, and extended operational lifetimes with high-power density (from μW to mW) in controlled manners. However, issues such as alignment, scattering, attenuation, absorption, and coupling of signals at tissues interface and limited penetration depth are yet to be resolved to achieve higher efficiency of power transfer. The comparisons of various types of energy systems are summarized in the Table 1.

In this perspective, we highlight several viewpoints, comparisons, challenges, associated research opportunities, and future directions for transient, biodegradable energy devices and systems. To reach an ultimate goal, various critical issues and several future approaches need to be considered, as follows. 1) For practical application of energy storage devices, improving the volumetric energy density is essential for higher energy storage to extend the operational time and improving the safety is the fundamental criteria for biomedical electronic devices. Higher energy conversion efficiency, power output, and durability are critical for energy harvesting and transfer systems in long-term applications; 2) Improving the intrinsic properties such as ionic or electronic conductivity, piezoelectric, or triboelectric properties of the organic materials via altering their molecular bonds through chemical modifications could be used as active materials for energy harvesting or transferring systems; 3) Development of transient, biodegradable electronics that could harvest, store, and transfer energy to power various ecofriendly, implantable, and/or ingestible devices will enable such devices to be more efficient.

| Table 1. Comparison between various energy systems. |
|-------------------------------------------------------------------------------------------------|
| **Categories** | **Output** | **Lifetime** | **Implantable site and depth** | **Biodegradability** | **Issues** |
| --- | --- | --- | --- | --- | --- |
| **Energy storage systems** | Batteries | High ED\(^{[a]}\) | Short | Unlimited | O\(^{[b]}\) | Slow charge/discharge rates |
| | Supercapacitors | High PD\(^{[b]}\) | Long | Unlimited | O | High self-discharge |
| **Self-powering systems** | Triboelectric | High OPV\(^{[c]}\) | Long | Limited | O | Large size, pulse output |
| | Piezoelectric | High OPV | Long | Limited | O | Large size, pulse output |
| | Galvanic | Low OPP\(^{[d]}\) | Short | Limited | O | Electrode oxidation and corrosion |
| | Biofuel | Low OPP | Short | Limited | O | Large size, oxygen diffusion/depletion |
| **Energy transfer systems** | PV | High OPP | Long | Limited | O | Heating issues |
| | Inductive coupling/RF | High OPP | Long | Limited | O | Heating and alignment issues |
| **Envisioned energy sources** | Thermoelectric | Low OPP | Long | Limited | Partial | Low thermal gradient |
| | Biopotentials | Low OPP | Long | Limited | Partial | Large size, ion selectivity issues |
| | Ultrasonic | High OPP | Long | Limited | Partial | Scattering and coupling issues |

\(^{[a]}\)ED, Energy Density; \(^{[b]}\)PD, Power Density; \(^{[c]}\)OPV, Output Voltage; \(^{[d]}\)OPP, Output Power; \(^{[e]}\)O, Biodegradable.
and powerful enough to perform a range of diagnostics and therapeutic treatments wirelessly; 4) Development of dissolvable polymer materials based on existing natural or synthetic materials to enhance structural, mechanical, and biochemical properties for energy systems is needed; 5) Microstructural engineering of materials, such as materials composition, doping, crystallinity, and porosity, could enable a wide range of tunability of dissolution rates and electrical functionality of transient, biodegradable devices; 6) Introducing the polar functional groups to existing high-performance materials by modifying chemical structures could improve their solubility in polar green solvents for use in green processing of electronic devices such as solution-processed organic PV (OPVs); 7) Development of nontoxic, low-cost fabrication techniques such as 3D printing of aqueous, biodegradable functional inks that consist of inorganic particles and a polymer matrix could provide unparalleled advantages in the rational structure designs of materials, devices, and their integration strategies that are essential for large-area processing, commercialization, and widespread use of green, transient, and biodegradable electronics; 8) Currently, evaluations of transient, biodegradable energy devices/systems are performed mostly in in vitro (in simulated biofluids) environments and/or small animal models; therefore, influences of complex biochemical, biothermal, and biomechanical in vivo environments (large animal models), on device properties such as operation stability and power output over a long period, are yet to be completely understood; 9) Furthermore, long-term influences on biological environments and devices/tissues interface must be further examined and quantitatively assessed to minimize or mitigate potential risks of materials and systems; and 10) By and large, each energy system has its own pros and cons; therefore, for significant enhancement of operational properties such as lifetime and output power, the ultimate key solution could be pursuing a hybrid energy system that consists of energy storage devices (supercapacitor or battery) integrated with an external energy receiving unit (ultrasound/RF-powered wireless module or PV cell) or an energy harvesting unit (TENG, piezoelectric, galvanic cell, or biofuel/potentials) that could power systems even when some of the units cannot work under unanticipated conditions.

Beyond the technological viewpoint, sustainability issues of energy devices are more concerned by society than ever before. As the scientists have made fruitful advancements in this field over the past decade, it is crucial to 1) reduce the big gap between the academia and industry; and 2) limit the complex regulatory landscape, would accelerate the transformation of novel innovations from laboratories to industrial applications and promote the implementation of transient, biodegradable energy system for sustainable future. It is undoubtful that the transient, biodegradable energy systems hold the huge potential to solve many of the current limits in terms of both fundamental and applied research.

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Rajaram Kaveti is currently a research assistant professor at the KU-KIST Graduate School of Converging Science and Technology at Korea University, South Korea. He received his Ph.D. in 2020 from the Division of Advanced Materials Engineering at Kongju National University, South Korea, and M.Sc. in physics from University of Hyderabad, India, in 2014. His current research focuses on design and development of soft, transient, biodegradable materials/electronics for disease monitoring, diagnostics, and treatment.
Seung Min Yang is a Ph.D. candidate in the KU-KIST Graduate School of Converging Science and Technology at Korea University. He received his B.S. in electronic engineering and in medical convergence engineering from Korea University, South Korea, in 2017. His current research interests include flexible, stretchable, transient, and biodegradable electronics.

Suk-Won Hwang is an associate professor at the KU-KIST Graduate School of Converging Science and Technology at Korea University, South Korea. He worked for Samsung Electronics Co., Ltd. (2005–2007) and obtained a Ph.D. (2013) under the guidance of Professor John A. Rogers, in the Department of Materials Science and Engineering at the University of Illinois at Urbana–Champaign. His research interests cover soft, bioresorbable materials/electronics for wearable devices, medical implants, and security applications.