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REVIEW

Technologies and applications in wireless biosensors for real-time health monitoring

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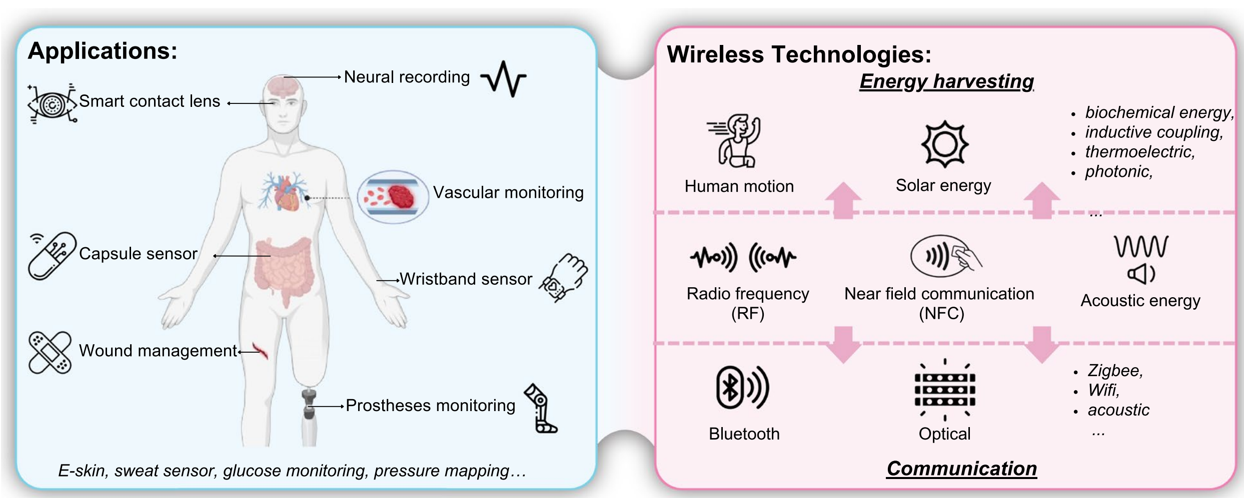
Abstract
Wireless biosensing has emerged as a critical technology due to its ability to provide real-time, continuous monitoring of physiological parameters without the constraints of wired connections. This review starts from the fundamental mechanisms of physical and chemical sensing in wireless biosensors, to the integration of advanced wireless technologies for energy harvesting and data communication, including Radio Frequency, Bluetooth, and other forms. Additionally, it covers diverse applications in wearable and implantable biosensors, such as cardiac monitoring, prosthetic enhancements, electronic skin and contact lenses. Attention is given to the emerging fields of osseosurface electronics and gastrointestinal capsule sensors, which represent significant advancements in non-invasive and minimally invasive health monitoring. The synergistic integration of these technologies paves the way for innovative diagnostic and therapeutic tools, promising improved patient outcomes and convenient healthcare solutions. This comprehensive overview aims to provide insights into the current state and future prospects of wireless biosensing technologies, underscoring their potential to be realized in various kinds of biosensors.

Graphical Abstract



Highlights
- Explores emerging capabilities of wireless biosensing technologies in providing continuous health monitoring
- Showcases advancements in energy harvesting and seamless data transmission techniques in wireless sensing platforms
- Dissects the diversified applications of wireless biosensors in the fields of precision medicine and point-of-care diagnostics

Extended author information available on the last page of the article

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Introduction

Wireless technologies have extended the capabilities of traditional sensors by eliminating the need for wired connections, thus enhancing mobility, convenience, and integration into everyday life [1]. The development of sensing techniques can be broadly classified into physical [2–4] and chemical mechanisms [5–7]. The advent of wireless technologies has significantly enhanced the functionality and applicability of these sensing mechanisms [8]. Additionally, energy harvesting techniques, including radio frequency (RF), acoustic energy, solar energy, and other innovative methods such as biomechanical and biochemical sources, provide sustainable power solutions for wireless sensors, ensuring their long-term operation without frequent battery replacement [9]. RF source is further classified into capacitive coupling, inductive coupling and far-field energy harvesting methods in detail. Thus, not only do wireless sensing technologies hold potential for biomedical settings, but their mechanisms also additionally support clean energy advancements. Furthermore, wireless communication technologies such as RFID, NFC, magnetic resonance coupling, Bluetooth and Bluetooth Low Energy (BLE), Zigbee, optical, Ultra-Wideband (UWB), and acoustic mechanisms are discussed, highlighting their significance in enabling efficient data transmission and integration with various devices and systems.

Wireless biosensors have become integral to point-of-care diagnostics and personalized medicine [10–12], with platforms ranging from cardiac monitoring to gastrointestinal disease detection. In addition to wearables, wireless biosensor designs also exist in implantable and prosthetic forms, with usages such as stethoscopes, ingestible capsules, and contact lenses, etc. [13–15]. Cardiovascular-focused devices such as smart patches and stethoscopes monitor heart rate, electrocardiogram (ECG), and cardiopulmonary signals, while prosthetics incorporate pressure and temperature sensors for enhanced functionality [16]. Electronic skin sensors and respiratory virus diagnosis systems wirelessly analyze physiological signals, while flexible RF biosensors non-invasively track blood flow, and implantable biosensors and smart contact lenses monitor biomarkers [17] and health conditions. Recent advancements also include the development of injectable, self-powered liquid bioelectronics using permanent fluidic magnets (PFMs), which provide a minimally invasive approach to cardiac monitoring. This technology eliminates the need for solid-state implants and offers a retrievable and conformal interface for real-time cardiovascular monitoring [18]. Additionally, fiber-shaped capacitive strain sensors improve hemodynamic monitoring, showcasing the versatile potential of wireless sensing technologies in healthcare [19].

The applications of these wireless electrochemical devices have become increasingly promising due to the enablement of the Internet of Things (IoT), which entails a wide network of connection sensors, actuators, identifiers, and products that interact with each other autonomously [20]. The hybrid IoT paradigm introduces constant interaction between electrochemical and biological sensing with the greater digital environment, which has numerous beneficial implications. This seamless integration of detection processes has allowed for the development of closed-loop wireless biosensor technologies, in which feedback systems consisting of control algorithms and sensors collaborate to deliver, for instance, electrical stimulation or drug delivery functionalities [21–23]. Though currently the wireless wearables market is still in its early developmental stages, the field is poised for future growth — the wearable biosensors market is estimated to reach $29,648.8 million USD in 2023 and is projected to grow to $65,400.2 million USD by 2033. The diversified functionalities of wireless biosensors give rise to applications in a wide range of commercial sectors, not only in healthcare and hospital settings. These include security, athletics and personal sport, food-chain regulation, and any division that requires the real-time wireless communication of biological analyses [24]. This paper serves to outline the technical intricacies within the field of wireless biosensors for real-time health monitoring, as well as share the current state of research surrounding applications in this realm.

Sensing mechanisms

Sensing mechanisms play a crucial role in wireless biosensors by enabling the detection and measurement of various parameters, primarily categorized into physical sensing and chemical sensing. These mechanisms are integral to the functionality of a wide range of devices and systems, from wearable health monitors to medical diagnostics and advanced research tools.

Physical sensing

Physical sensing mechanisms detect changes in physical parameters such as temperature [25–27], pressure [28–30], motion [31–33], and light [34–36]. These sensors are fundamental to numerous applications, including wearable devices that monitor vital signs and track physiological conditions. Physical sensors include thermal sensors, piezoelectric sensors, accelerometers, and optical sensors, each designed to measure specific physical changes with high precision. These sensors provide critical data that can improve patient care and support advanced medical research [37–39].

To measure exposure to electromagnetic radiation, the wireless and miniaturized dosimeters monitor [40] achieves the goal by using optical metrology approaches, where light-based methods are employed. The core of this approach is photodiodes, which are semiconductor devices that convert light into electrical signals. The intensity of the light exposure is directly proportional to the current generated by the photodiodes, allowing for precise quantification (Fig. 1A). These photodiodes are integrated into a flexible and miniaturized system that operates without the need for batteries. Instead, they utilize NFC technology, which provides wireless power transfer and data communication. NFC-enabled hardware, such as smartphones or specialized readers, interacts with the biosensor to both power the device and read the accumulated data. This system allows the dosimeter to collect and store data on light exposure over time, ensuring comprehensive monitoring. The collected data is stored as a voltage across a supercapacitor, which can be read wirelessly. The integration of a reset function enables the device to manage storage capacity effectively, maintaining accurate measurements over extended periods. Temperature sensing is also incorporated into the design, with integrated sensors that measure and record temperature alongside light exposure. This dual-functionality is essential for applications where both light and temperature impact the monitored condition, such as in phototherapy treatments.

Normally, these sensors are expected to be thin, flexible, and skin-like, allowing them to conform seamlessly to the human body. This design for full-body pressure and temperature mapping [41] not only enhances comfort for the user but also ensures accurate and continuous data collection by maintaining close contact with the skin (Fig. 1B). For pressure sensing that utilizes piezoresistive materials to measure,

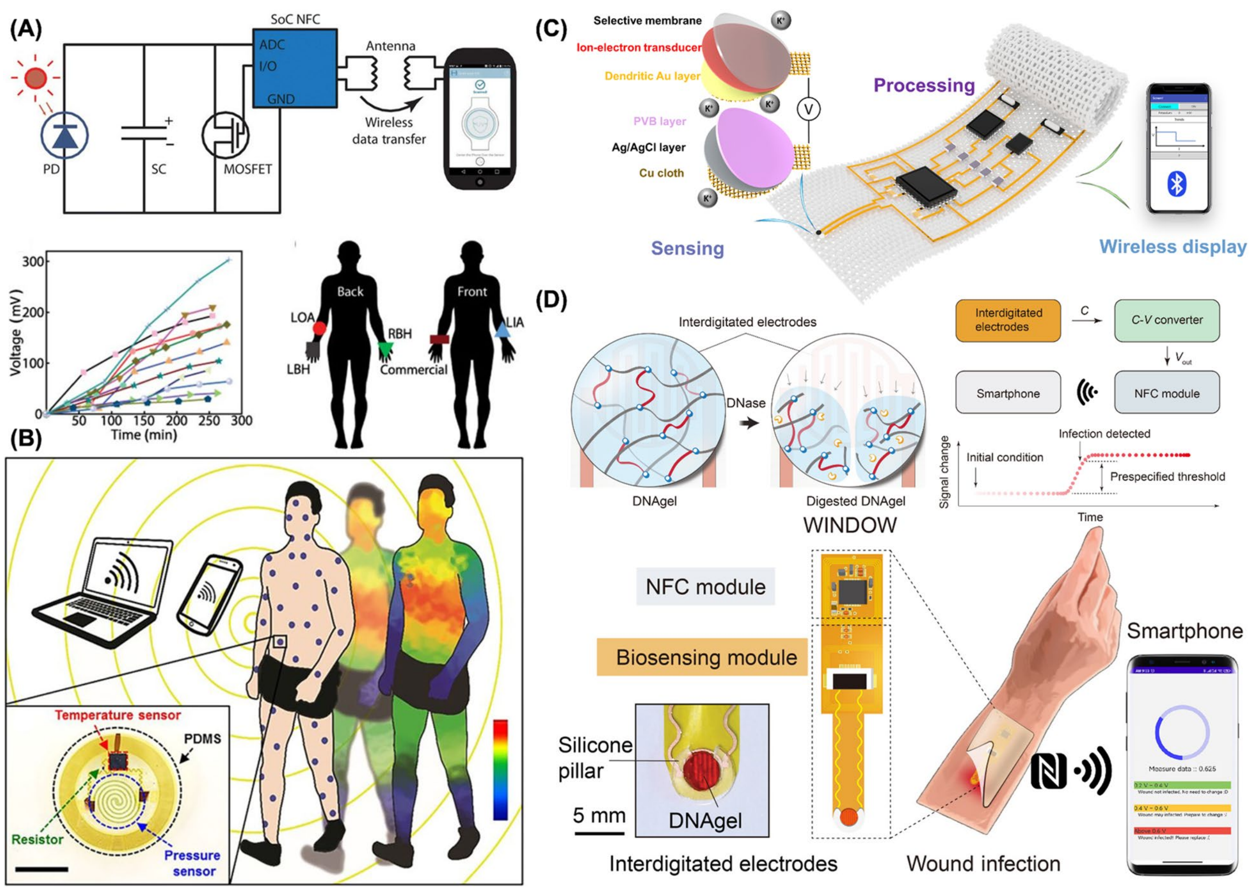

Fig. 1 **A** Diagram of a battery-free wireless dosimeter showing the integration of a photodiode, supercapacitor, and NFC module for sensing and data transmission. And the data below illustrate the voltage response over time and the positioning of sensors on different body parts. **B** Illustration of battery-free, wireless sensors for full-body pressure and temperature mapping. The system includes temperature and pressure sensors embedded in PDMS. **C** Schematic of a monolithically integrated wristband for wireless sweat potassium analysis. The wristband features a multi-layered sensor with an ion–electron transducer and a Bluetooth module for real-time data display on a mobile device. **D** Design of a wireless, battery-free wound infection sensor based on DNA hydrogel. The system uses interdigitated electrodes to detect DNA hydrogel degradation by DNase, with data transmission via NFC

incorporating a thin, monocrystalline silicon membrane patterned into specific shapes, such as spirals, to optimize sensitivity and uniformity of strain distribution when pressure is applied. The piezoresistive effect, where mechanical strain induces a change in electrical resistance, is the fundamental mechanism through which these sensors operate. The change in resistance is then converted into an electrical signal that can be transmitted wirelessly. For temperature sensing, the design includes a resistance thermometer detector integrated into the sensor's circuitry. These detectors are capable of precise measurements by detecting minute changes in resistance that correlate with temperature fluctuations. To ensure accurate temperature readings, the sensors are designed with materials that have minimal thermal mass and excellent thermal conductivity, allowing them to quickly reach thermal equilibrium with the skin. NFC is used for power transfer and data communication. The integration of these design elements allows for the development of advanced wireless biosensors capable of full-body monitoring. These sensors can be distributed across various anatomical locations to provide comprehensive spatiotemporal maps of physiological parameters.

Chemical sensing

Chemical sensing mechanism in wireless biosensors is critical for detecting and quantifying specific biochemical markers within the body. These sensors utilize a range of techniques, including electrochemical sensing [42–44], optical sensing [45–47], and enzymatic reactions [48–50], to achieve high sensitivity and specificity. Electrochemical sensors measure electrical signals produced by biochemical interactions, optical changes can be detected by eyes or optical sensors, and enzymatic sensors exploit biochemical reactions catalyzed by enzymes. Integrating these chemical sensing technologies with wireless communication systems enables real-time, continuous monitoring of health parameters, enhancing personalized healthcare and early disease detection.

A common design in wireless sensors is using chemical sensing to detect specific chemicals and Bluetooth to achieve wireless communication. This design [51] focuses on the integration of chemical sensors within a wearable format, such as a wristband, to non-invasively monitor biomarkers in bodily fluids like sweat. The primary method for sensing involves electrochemical sensors, which are used at detecting various ions and molecules due to their high sensitivity and specificity (Fig. 1C). The wristband features an ion-selective electrode (ISE) and a reference electrode, typically made from silver/silver chloride (Ag/AgCl), to form a two-electrode system. The ISE is coated with a selective membrane that responds to specific ions in the sweat, generating a potential difference relative to the reference electrode. This potential difference is measured and correlated to the concentration of the target ion, such as potassium ($K+$), providing real-time data on the wearer's electrolyte levels. To ensure the robustness and accuracy of the sensor, the design incorporates materials like poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT) for the ion-to-electron transducer layer. This layer enhances the stability of the sensor by minimizing signal drift and improving the longevity of the device. The electrodes are typically fabricated using advanced methods like polymer-assisted metal deposition (PAMD), which ensures high conductivity and mechanical durability. The wireless transmission of data is facilitated by a Bluetooth module integrated into the wristband. This module allows for the continuous transmission of biosignals to a mobile device, where a custom application can display the data in real time.

Also, biological principles are also used in this field. The design of the wireless, battery-free wound infection sensor [52] demonstrates the innovative use of DNA hydrogel (DNAgel) for biochemical sensing, integrating advanced wireless technologies to enable real-time monitoring and detection of wound infections. The core component, DNAgel, is engineered to respond selectively to deoxyribonucleases (DNase) secreted by pathogenic bacteria, such as Staphylococcus aureus, a common cause of wound infections (Fig. 1D). Upon exposure to DNase, the DNAgel degrades, altering its dielectric properties and enabling detection of bacterial presence through capacitive sensing. This degradation process results in a change in the capacitance of an interdigitated electrode embedded within the sensor, which is then wirelessly transmitted to a smartphone or similar device. The wireless transmission is facilitated through NFC for short-range wireless communication and power transfer. To further improve user experience, the sensor employs a flexible, thin form factor that can be seamlessly integrated into wound dressings.

Energy harvesting

Energy harvesting is a critical aspect of wireless biosensors, enabling continuous and autonomous operation without the frequent need for battery replacements [53–56]. This approach harnesses ambient energy from various sources to power the sensors, significantly enhancing their usability and lifetime. Various kinds of RF are prominent methods, utilizing electromagnetic waves to generate power [57–59]. Other energy harvesting methods include acoustic energy [60–62], biomechanical energy [63–65], biochemical energy [66–68], and solar energy [69–71] etc.. Emerging technologies such as piezoelectric [72–74] and thermoelectric energy harvesting [75–77] are also gaining attention. Piezoelectric devices convert mechanical stress into electrical energy,

Table 1 Comparison of RF energy harvesting mechanisms

Mechanism	Medium	Range	Efficiency	Application	Refs	Illustration
Capacitive Coupling	Electric Field	Short (millimeters)	Moderate to Low	Low-power devices, sensors	[78]	Fig. 2A
Inductive Coupling (IC)	Magnetic Field	Short (centimeters)	High (close range)	Wireless charging, implants	[79]	Fig. 2B
Magnetic Resonance Coupling (part of IC)	Magnetic Field (Resonance)	Medium (meters)	Moderate	Medical devices, EV charging	[80]	Fig. 2B
Far-Field RF Energy Harvesting	Electromagnetic Waves	Long (meters to kilometers)	Low	Remote sensors, IoT	[81]	Fig. 2C

while thermoelectric generators exploit temperature gradients. These developing methods promise to further enhance the versatility and efficiency of wireless biosensors, ensuring they remain powered in a wide range of conditions. By integrating these diverse energy harvesting techniques, wireless biosensors can achieve greater autonomy and reliability, making them invaluable in continuous health monitoring and other applications.

Radio Frequency (RF)

Among the various methods of energy harvesting, RF energy harvesting stands out for its versatility and effectiveness in powering wireless biosensors. This approach captures and converts ambient electromagnetic energy into electrical power, which can be harvested through various techniques.

RF energy harvesting technologies can be broadly categorized into near-field and far-field mechanisms, each suited for specific applications. Near-field techniques, such as capacitive coupling, inductive coupling, and magnetic resonance coupling, rely on electric or magnetic fields to transfer energy over short to moderate distances. Capacitive coupling uses electric fields between conductive plates, effective at very short distances for low-power devices and sensors. Inductive coupling, which uses magnetic fields generated by coils, is highly efficient over short ranges and is commonly applied in wireless charging and medical implants. Magnetic resonance coupling extends inductive coupling's range by using resonant frequencies, allowing for more efficient energy transfer over moderate distances, such as in electric vehicle (EV) charging and medical devices. On the other hand, far-field techniques, like far-field RF energy harvesting, capture electromagnetic waves transmitted over long distances using antennas. Although this method enables energy transfer over meters to kilometers, it operates with significantly lower efficiency, making it suitable for remote sensors and IoT devices. The table below compares these mechanisms, highlighting their energy transfer medium, range, efficiency, and applications (Table 1).

Capacitive coupling

Capacitive coupling is one method of RF energy harvesting that utilizes electric fields between conductive plates separated by a dielectric material [82–84]. This method is particularly effective for low power transfer, making it suitable for applications in biosensors [85]. Additionally, Capacitive Coupling Human Body Communication (HBC) offers a promising approach by using the human body as a medium to transmit and harvest energy from ambient electromagnetic waves, providing an efficient and placement-independent power source for wearable biosensors [86–88].

The design of the body-coupled interactive fiber [89] that can be used in wireless biosensors offers a novel approach to capacitive coupling for energy harvesting. This fiber integrates electronic assemblies into a single, soft, and flexible strand, eliminating the need for rigid components such as silicon chips and batteries (Fig. 2D). The fiber consists of three functional layers: an antenna core made of silver-plated nylon fibers to induce alternating electromagnetic (EM) fields, a dielectric layer of barium titanate (BaTiO3) mixed resin for energy storage, and an optical layer of zinc sulfide (ZnS) mixed resin for visual feedback. This design allows the fiber to perform wireless transfer, sensory processing, and feedback functions seamlessly integrated into modern textile weaving techniques. The primary energy harvesting method employed is capacitive coupling, utilizing the human body to couple ambient EM energy from the environment. The fiber generates bound charge pairs between the body and the electronic fiber, which can alternate between bound and radiation states to emit wireless sensing signals. This mechanism effectively captures ambient EM energy dissipated from sources such as smartphones, power cables, and even fabric friction. The energy is collected through a closed loop involving the fiber, the human body, and the ground, allowing for efficient energy transfer without the need for an external power source. The fiber's design allows it to transmit both optical and electrical signals wirelessly, leveraging Faraday's and Ampere-Maxwell's laws for EM wave generation. This chipless modulation strategy manipulates the

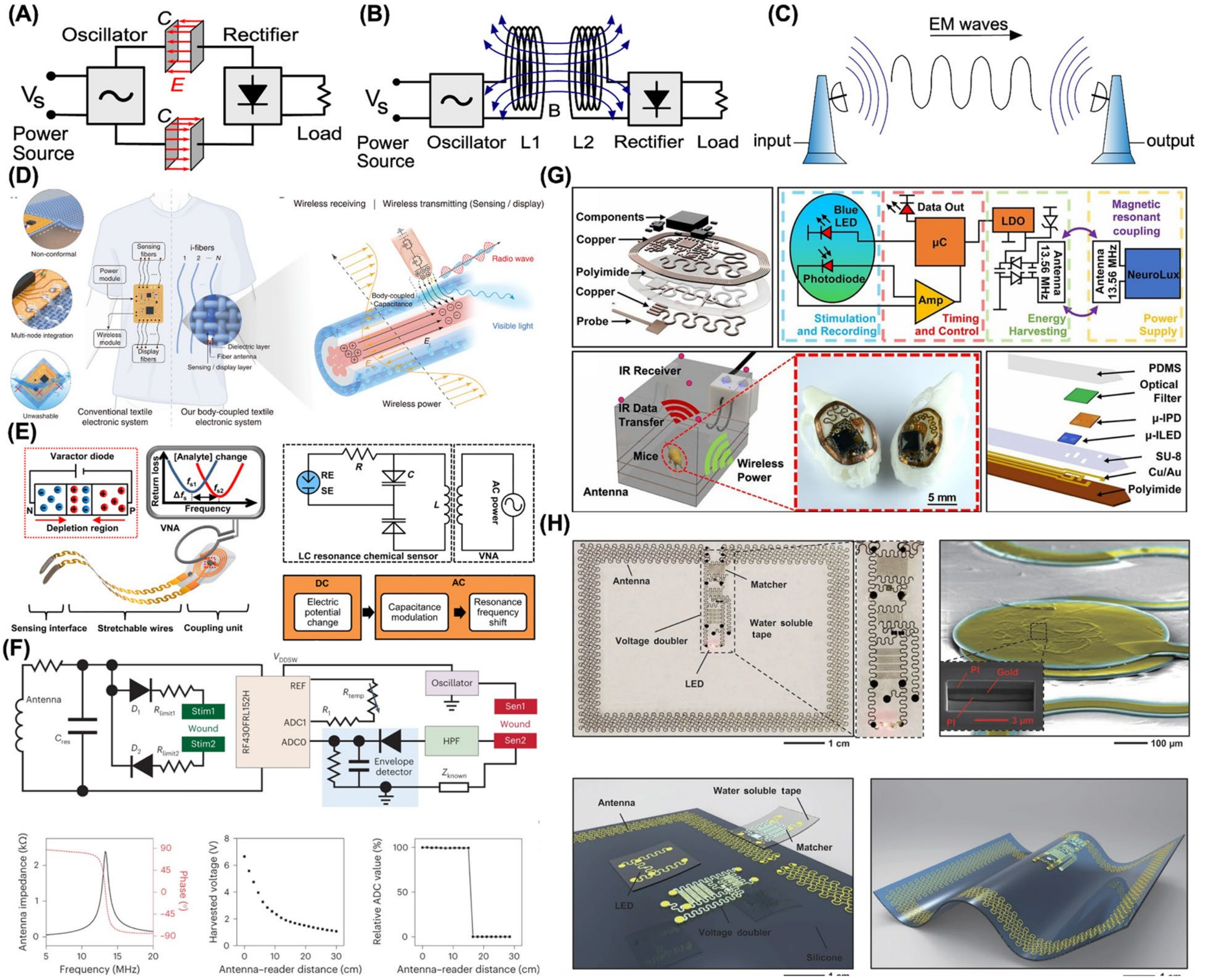

Fig. 2 **A**, **B**, and **C** Mechanism illustrations of capacitive coupling, inductive coupling, and far-field RF energy harvesting (**D**) Schematic of a body-coupled textile electronic system showing wireless power transmission through body-coupled capacitance for sensing and display compared with conventional method, highlighting the integration of sensing and display fibers with a dielectric layer for capacitive coupling. **E** Diagram of an LC resonance chemical sensor utilizing inductive coupling for energy harvesting. The system harvests AC power through a coupling unit, with an LC circuit modulating capacitance changes detected by a vector network analyzer (VNA). **F** Schematic of the wireless smart bandage system for energy harvesting and wound monitoring. The RF-harvested voltage is optimized through an antenna resonating at 13.56 MHz. Data figures show antenna impedance and phase across frequency, harvested voltage, and relative ADC value as functions of antenna-reader distance. **G** Layout of a wireless, battery-free subdermally implantable photometry system. The device uses magnetic resonant coupling at 13.56 MHz for energy harvesting, with power supply and data transmission modules integrated for chronic neural recording. **H** Structure and implementation of an epidermal far-field RF energy harvesting system. The system features a loop antenna, matcher, and voltage doubler on a flexible substrate, enabling wireless power transfer to an integrated LED

intrinsic radial capacitance of the fiber to tune the frequency and amplitude of the wireless signals. The fiber can transmit signals effectively over distances up to 30 m, making it suitable for various applications, including tactile sensing and communication.

Inductive coupling

Inductive coupling is another prominent technique, relying on magnetic fields generated by an AC current in a primary coil [90–92]. This changing magnetic field induces a voltage in a nearby secondary coil, enabling efficient energy transfer over short distances [93–95].

A battery-free, tuning circuit-inspired wireless sensor system for detecting multiple biomarkers in bodily fluids [96] takes advantage of the principles of inductive coupling to achieve efficient energy harvesting, which is critical for its battery-free operation. The core design features an inductor-capacitor (LC) resonance circuit composed of a coil and varactor diodes. These varactor diodes convert changes in electric potential, caused by biochemical events, into variations in capacitance, which lead to shifts in the resonance frequency of the LC circuit (Fig. 2E). This allows for the precise detection of various biomarkers in bodily fluids. The energy harvesting in this system is achieved through inductive coupling, where an external transmitter coil generates an electromagnetic field that is captured by a receiver coil embedded in the sensor. The loop antenna acts as the coupling unit, ensuring that the sensor receives adequate power to operate continuously without the need for batteries. This is particularly advantageous for wearable and implantable applications, where replacing batteries can be impossible. The design also addresses potential issues related to interference from electromagnetic fields. By using extended wires to connect the coupling unit and the sensing interface, the system minimizes the impact of electromagnetic interference on the accuracy and reliability of the sensor's measurements. This separation ensures that the sensor can maintain high performance even in complex biological environments.

High-Frequency Radio-Frequency Identification (HF RFID) operates within the 3 MHz to 30 MHz range [97, 98], with 13.56 MHz being the most widely used frequency due to its optimal balance of range and data transfer rate, also called NFC [99, 100]. HF RFID technology utilizes inductive coupling for efficient short-range energy harvesting and communication. In an HF RFID system, the reader generates a magnetic field that induces an electric current in the antenna of a passive tag when it enters the field. This induced current powers the tag, enabling it to transmit data back to the reader [101, 102].

An advanced wireless, closed-loop smart bandage for wound care [103] integrates energy harvesting methods to ensure continuous operation without traditional batteries. They incorporate a flexible printed circuit board (FPCB) that houses an energy-harvesting antenna, a microcontroller unit (MCU), a crystal oscillator, and filter circuits (Fig. 2F). The antenna, designed to resonate at 13.56 MHz, is inductively coupled with an external radiofrequency identification (RFID) reader. This setup not only powers the biosensor but also facilitates continuous monitoring of physiological parameters such as wound impedance and temperature via an NFC transponder under the ISO 15693 protocol. The wireless nature of this design allows for the seamless integration of sensing and stimulation circuits without the discomfort associated with wired connections. To enhance energy transfer efficiency and ensure robust operation, a low-impedance hydrogel electrode based on poly (3,4-ethylenedioxythiophene) sulfonate (PEDOT) is employed. This dual-conducting hydrogel provides superior charge injection capabilities and adheres well to the skin, which is critical for reliable signal transduction and energy harvesting. Furthermore, the hydrogel's adhesive properties can be controlled thermally, enabling easy removal and reducing the risk of secondary skin damage. The energy harvested is used to power both the sensing and stimulation functions of the biosensor. Continuous monitoring is achieved through sensors embedded in the FPCB that measure impedance and temperature.

Magnetic resonant coupling is an advanced form of inductive coupling that enhances energy harvesting by using resonance to improve the efficiency and range of wireless power transfer [104–106]. Resonance is a phenomenon that occurs when a system is driven by its natural frequency, causing it to oscillate with maximum amplitude due to the efficient transfer of energy. Both the primary and secondary coils are designed to the same resonant frequency, allowing the magnetic field generated by the primary coil to resonate with the secondary coil. This resonance amplifies the energy transfer process, enabling efficient power transmission over greater distances compared to traditional inductive coupling. This method is ideal for applications requiring reliable and medium-range energy harvesting [107–109].

The wireless, battery-free subdermally implantable photometry system [110] represents an advancement in neural activity recording technology, particularly in its innovative use of energy harvesting methods. This system uses magnetic resonant coupling to achieve efficient and reliable wireless power transfer. The design incorporates a millimeter-scale receiving antenna implanted subdermally, which is tuned to resonate at 13.56 MHz, matching the frequency of an external primary antenna encircling the experimental arena (Fig. 2G). When the primary antenna generates a magnetic field, the resonant frequency alignment between the primary and receiving antennas maximizes energy transfer. This magnetic field induces a current in the receiving antenna, which is then rectified and regulated to provide a stable direct current (DC) power supply for the device's electronic components. The rectifier circuit plays a crucial role by converting the alternating current (AC) induced in the antenna into DC, ensuring that the energy harvested is usable for the system's operations. The harvested energy powers the integrated microcontroller unit (MCU), which coordinates the functions of the photometry system, including the excitation of genetically encoded calcium indicators (GECIs) and the detection of fluorescence signals. Additionally, the energy supports the operation of a low-power infrared (IR) LED for wireless data communication. This efficient energy harvesting process enables continuous and stable operation of the photometry system, which is essential for chronic neural recording in freely moving objects. The design's reliance on magnetic resonant coupling allows for significant improvements in energy transfer efficiency and range compared to traditional inductive coupling methods. Furthermore, it can deliver higher power levels required for the device's continuous operation, which NFC cannot provide due to its lower power capabilities and very short operational range. The system's compact and flexible construction ensures minimal impact on the subjects, maintaining high performance even during dynamic movements.

Far-field RF energy harvesting

The far-field RF energy harvesting method allows the device to capture energy over distances of several meters, providing a continuous and reliable power source [111–113]. This method utilizes RF signals from sources like mobile phones, Wi-Fi networks, and broadcast stations, making it ideal for low-power devices where battery replacement is inapplicable.

The development of a skin-attachable, stretchable system for wireless human motion monitoring utilizes advanced energy harvesting techniques to free the need for batteries [113]. The far-field RF energy harvesting method here employs a modularized collection of ultrathin antennas, rectifiers, and voltage doublers (Fig. 2H). The energy harvesting process begins with the ultrathin, serpentine-structured antennas, which are specifically designed to capture RF signals from the environment. These antennas are optimized for flexibility and stretchability, allowing them to maintain efficient energy capture even under mechanical deformation. The antennas are capable of harvesting RF energy from a remote source. Once the RF signals are captured by the antennas, the energy harvesting unit plays a crucial role. This unit includes rectifiers that convert the AC signals from the RF energy into DC. Rectification is essential because the electronic components of the biosensor require a stable DC power supply to function correctly. The rectifiers used in this system are designed to operate efficiently at the low power levels typically associated with ambient RF energy. To further enhance the power output, the system incorporates voltage doublers. These components increase the voltage of the rectified DC power, ensuring that the biosensor receives a stable and sufficient energy supply. The combination of rectifiers and voltage doublers maximizes the efficiency of the energy harvesting process, enabling the device to operate effectively even with the low power levels harvested from ambient RF sources.

Acoustic energy

Acoustic energy harvesting is an emerging method that captures energy from sound waves and converts it into electrical power. This technique leverages the mechanical vibrations produced by sound waves, typically within the audible frequency range, to generate electricity through various transduction mechanisms. Acoustic energy harvesting is particularly attractive for applications over longer distances compared to near-field RF energy transferring and in environments rich with sound, where noise is abundant and can be repurposed as a renewable energy source.

The design of a wireless, battery-free subdermally implantable photometry system [114] emphasizes the innovative use of acoustic energy harvesting. This system employs ultrasonic waves to wirelessly power and communicate with mm-scale devices implanted in the body, eliminating the need for traditional batteries (Fig. 3A). The core of this design is a piezoelectric transducer that converts ultrasonic energy into electrical power. The external ultrasonic transducer, positioned outside the body, emits a series of high-frequency pulses. These pulses generate mechanical vibrations in the piezoelectric crystal of the implanted device, which are then converted into electrical energy through the piezoelectric effect. The harvested electrical energy is subsequently rectified and regulated by the system's circuitry to provide a stable DC supply. This power is essential for the operation of the photometry system's electronic components, including sensors and communication modules. The ultrasonic energy harvesting method not only ensures continuous and reliable power delivery but also enables the device to operate efficiently deep within the body, where other wireless power transfer methods, such as RF, would be less effective due to significant attenuation and absorption by biological tissues. In this system, the rectifier circuit is crucial as it transforms the AC generated by the piezoelectric transducer into a usable DC power supply. This process involves filtering and stabilizing the converted energy to ensure it meets the operational requirements of the integrated microcontroller unit (MCU) and other electronic components. The MCU, in turn, processes data from the sensors and manages the wireless transmission of information via ultrasonic backscatter, enabling real-time monitoring and data collection.

Another design using acoustic energy is a flexible, stretchable system for simultaneous acoustic energy transfer and communication [115] in the field of implantable medical devices. This system utilizes ultrasound to wirelessly transfer energy and facilitate communication between the device and external equipment (Fig. 3B). The core component of this design is the acoustic transducer, which converts ultrasonic waves into electrical power. The external ultrasonic transducer, positioned outside the body, emits high-frequency ultrasound waves that travel through biological tissues with minimal attenuation. When these ultrasound waves reach the implanted device, they induce mechanical vibrations in a piezoelectric transducer embedded within the system. And the generated electrical energy is subsequently rectified and regulated to produce a stable DC power supply, which is essential for the continuous operation of the device's electronic components, including sensors and communication modules. The harvested DC power is managed by an integrated power management unit (PMU) that not only regulates the voltage but also distributes the power to various subsystems within the implant. This includes powering advanced sensors that monitor physiological parameters such as temperature, pressure, and biochemical markers. Additionally, the PMU supports the operation of a communication module that uses ultrasound waves to send data back to the external receiver, enabling real-time monitoring and data analysis.

Biomechanical energy

Biomechanical energy harvesting is an innovative method that captures mechanical energy generated by human activities and converts it into electrical power [116–118]. This approach collects the kinetic energy produced during everyday movements such as walking, running, bending, and other physical activities. By utilizing various transduction mechanisms, such as piezoelectric and triboelectric systems, human motion energy harvesters can generate a sustainable and continuous power supply for wearable and implantable electronic devices. These systems are especially advantageous in continuous monitoring scenarios where long-term, uninterrupted operation is critical. The captured biomechanical energy can power low-energy biosensors that track vital signs.

Energy from human motion is used properly in the design of a wireless, battery-free wearable sweat sensor [119]. This system harnesses mechanical energy generated from human movements, converting it into electrical power using a flexible printed circuit board (FPCB) based freestanding triboelectric nanogenerator (FTENG) (Fig. 3C). The FTENG operates on the principle of triboelectricity, where mechanical motion between different materials generates electrical charges due to contact electrification and electrostatic induction. The design integrates an interdigital stator, and a grating-patterned slider made from materials with differing triboelectric properties, such as polytetrafluoroethylene (PTFE) and copper. As the user moves, these components slide against each other, creating mechanical vibrations that induce an AC in the circuit. This AC is then rectified into DC by an internal rectifier circuit, ensuring a stable power supply for the device's electronic components. The energy harvesting process is facilitated by the optimized design of the FTENG, which includes a high charge density and a robust structure capable of withstanding repeated mechanical stress. The harvested energy is stored in capacitors and managed by a power management integrated circuit (PMIC), which regulates the voltage and ensures continuous power supply. This energy powers the sweat sensor's microfluidic system, biosensors, and Bluetooth Low Energy (BLE) module, enabling real-time data acquisition and wireless transmission.

In biomechanical energy harvesting systems designed for wireless biosensors, the integration of magnetoelastic fibers into textile-based structures presents an efficient and practical approach. The primary energy harvesting mechanism relies on the magnetoelastic effect, where soft, flexible fibers embedded with magnetic nanoparticles generate electrical power through mechanical deformation [120]. When subjected to biomechanical forces, such as body movements, these fibers undergo deformation, altering the alignment of magnetic dipoles (Fig. 3D). This shift in dipole orientation induces changes in the magnetic flux, which is subsequently converted into electrical energy via woven conductive yarns. The design employs a two-step energy conversion process—first, mechanical-to-magnetic conversion through the magnetoelastic fibers, and second, magnetic-to-electrical conversion using conductive yarns. These conductive yarns, typically silver-coated nylon, are woven into the textile structure, allowing for large-scale electricity generation while maintaining flexibility and wearability. Notably, the design is humidity-resistant, making it suitable for long-term, real-world applications where exposure to sweat or fluids is inevitable. The harvested energy can power low-energy wireless communication technologies, such as Bluetooth, enabling continuous, real-time transmission of physiological data without the need for frequent battery replacements. This design enhances the practicality and sustainability of wireless biosensors in real-time health monitoring applications.

Biochemical energy

Biochemical energy harvesting taps into the body's natural metabolic processes to generate power for wireless biosensors. By utilizing biofuel cells that convert substances like glucose and oxygen into electricity, these systems create a continuous, self-sustaining energy supply. This method is particularly useful for implantable biosensors, where regular battery replacement is impractical. Biochemical energy harvesting enables long-term operation by drawing energy from natural bodily functions, reducing maintenance and enhancing patient comfort. This approach holds promise for powering sensors that monitor physiological parameters, such as glucose levels, without disrupting normal biological processes. Its integration into wireless biosensor systems allows for more reliable monitoring in real-time health applications.

A notable example of this approach is the development of a biofuel-powered soft electronic skin (e-skin) [121] designed for multiplexed and wireless sensing applications, particularly in human–machine interfaces. This innovative design harnesses energy from human perspiration using highly efficient lactate biofuel cells (BFCs) (Fig. 3E). The core component of the e-skin is the biofuel cell array, which comprises bioanodes and cathodes modified with nanomaterials to enhance their electrochemical performance. These cells operate by catalyzing the oxidation of lactate, a common component in human sweat, into pyruvate at the bioanode. Simultaneously, oxygen is reduced to water at the


(A)
Signal generator
Power amplifier
Ultrasonic transducer
Demodulation
Signal amplifier
Ultrasonic transducer
External
Implanted
Ultrasonic transducer
Rectifier circuits
Energy management
Internal MCU
Modulation
Ultrasonic transducer
Biosensor
(B)
ASIC
FPGA
TX
RX
Switch
Transceiver board
Transducer
PC
G,H
Nerve or Muscle
50 mV
20 mV
Filter
Rectify
Integrate
1 mV
2 ms
(C)
Wearable sweat sensor system
Wireless transmission
Sweat biosensing
Signal processing
Energy harvesting
Health status alarm
FPCB stator
FPCB slider
PTFE
FTENG
Sensor patch
Flexible circuitry
Copper
PTFE
ENIG
Polyimide
(D)
Wearable electronic
Textile MEG
Magnetic field variation
With perspiration
Under water
Pulse wave profile
Pressure (kPa)
Time (s)
(E)
Lactate
Pyruvate
LOx
TTF-MDB
Pt-Co
Sweat
Biofuel cell
Sensor
Sweat-powered electronic skin
Urea
Temp
Glucose
Reference
Sensor 1
Sensor 2
Bioanode
Cathode
Au
h-Ni
rGO/h-Ni
TTF-MDB-CNT/rGO/h-Ni
Potential (V)
40 mM
20 mM
0 mM
P (mW cm⁻²)
Potential (V)
(F)
Sunlight
Indoor light
FPSC
Quasi-2D perovskite
LumiStat
Battery-free autonomous wearable biosensor
PI
Biosensors
Carbagel
PET/M-tape
Skin
Sweat

◂**Fig. 3** **A** Schematic of a wireless neural recording system utilizing ultrasonic energy harvesting, detailing the flow of ultrasonic energy and its conversion to electrical power for neural recording. Time traces of signals highlight the system's backscatter mechanism for data communication. **B** The system includes an external ultrasonic transducer for power generation, rectifier circuits, and energy management modules for efficient energy harvesting and wireless communication. **C** Illustration of a wearable sweat sensor system powered by human motion. The freestanding triboelectric nanogenerator (FTENG) efficiently harvests energy through sliding motion, enabling wireless transmission of biosensing data for real-time health monitoring. **D** Textile magnetoelastic generator (MEG) integrated into a wearable electronic for biomechanical energy harvesting. The MEG demonstrates reliable pressure sensitivity, generating electrical signals in response to varying pressures, and remains functional in both perspiration and underwater conditions, as shown by pulse wave profiles and current-pressure response. **E** Schematic of a sweat-powered electronic skin for real-time health monitoring. The lactate biofuel cell harvests energy from sweat, enabling wireless transmission of metabolic data to a mobile interface. Diagrams illustrate the enzymatic reactions and nanomaterial-based electrode modifications that facilitate efficient energy conversion. **F** An autonomous wearable biosensor powered by flexible perovskite solar cells (FPSC) for continuous, battery-free health monitoring. The device uses ambient light (both sunlight and indoor light) to power the biosensor, which wirelessly transmits real-time physiological data such as glucose, pH, temperature, and sweat rate to a mobile app for health tracking

cathode, generating a stable current. This redox reaction is facilitated by immobilized enzymes and nanostructured materials, which increase the surface area and improve the electron transfer rates. The electrical energy produced by the BFCs is then rectified and regulated to provide a stable DC power supply, crucial for the continuous operation of the device's electronic components. These components include a microcontroller, biosensors for metabolic markers (such as glucose, urea, and ammonium), and a BLE module for wireless data transmission. The e-skin's power management system is designed to optimize energy usage, ensuring that the harvested power is efficiently utilized for sensing and communication tasks. The design also incorporates a flexible and stretchable polymeric substrate that conforms to the skin, maintaining intimate contact for accurate sensing. The use of microfluidic channels enhances the sampling of fresh sweat, ensuring a continuous supply of biofuel to the cells and maintaining the stability of the power output.

Solar energy

Solar energy offers a sustainable approach to powering wireless biosensors used in various electronics. By integrating photovoltaic cells into wearable or implantable devices, solar energy can be converted into electrical power from ambient light, providing a continuous energy source. This method reduces the reliance on traditional batteries and enables long-term operation of biosensors. The flexibility and scalability of thin-film solar cells make them ideal for integrating into various biomedical applications, where lightweight and adaptable designs are crucial. Solar energy harvesting is particularly beneficial in outdoor or well-lit environments, where it can complement other energy sources, enhancing the overall efficiency and lifespan of wireless biosensor systems.

An example is the use of flexible perovskite solar cells (FPSC), which offer a high-power conversion efficiency (PCE) across varying light conditions, including both bright outdoor sunlight and low indoor light [122]. These cells employ a quasi-2D perovskite layer that absorbs light and generates electron–hole pairs, which are then separated and transported by electron and hole transport layers to generate electricity (Fig. 3F). The design integrates these solar cells with a highly efficient power management system, ensuring smooth energy transfer from the solar cell to the biosensor's electronics. The power generated is stored in capacitors or directly powers the biosensor's circuits. A typical configuration involves a flexible substrate, such as polyethylene terephthalate (PET), which provides mechanical stability while allowing the device to remain lightweight and wearable. The perovskite layer itself is optimized for high light absorption and low recombination rates, improving the overall efficiency of energy transfer. Once the solar energy is converted into electrical power, it is used to drive the biosensor's monitoring functions, as well as low-power wireless communication technologies like Bluetooth Low Energy (BLE). This enables real-time data transmission from the biosensor to external devices, such as smartphones or medical systems, without requiring an external power source.

Wireless communication

The adoption of wireless communication technologies in wearable, implantable, and injectable devices signifies a transformative shift in medical diagnostics and therapeutic monitoring. As the paradigm of healthcare moves towards more personalized and preemptive treatments, the role of wireless communication becomes increasingly critical. These technologies enable real-time data transfer from devices directly to healthcare providers or monitoring systems, facilitating timely interventions and continuous patient monitoring outside conventional clinical settings.

This transition is driven by the need for minimal patient intrusion and enhanced quality of life, allowing individuals to receive care without the constant need for physical healthcare visits. Furthermore, wireless communication empowers the integration of medical devices with everyday personal technology, creating a seamless health management ecosystem. In this section, we present various wireless communication technologies, each with unique capabilities in terms

Table 2 Comparison of wireless data communication technologies in biosensor application

	RFID	NFC	Magnetic Resonant Coupling	Bluetooth	Bluetooth Low Energy (BLE)	Zigbee	Ultra-Wide-band (UWB)	Optical
Frequency Band	120—140 kHz 13.56 MHz 868—956 MHz	13.56 MHz	Application dependent	2.4 GHz	2.4 GHz	2.4 GHz 915 MHz 868 MHz	3.1 GHz to 10.6 GHz	3 kHz to 3000 GHz
Working Range	up to 12 m (passive) 100 m (active)	up to 10 cm	Antenna dependent	up to 100 m	< 100 m	up to 100 m	< 100 m	10—30 m
Communication Rate	100 kb/s	106 kb/s 212 kb/s 424 kb/s	Up to few hundred kbps	~ 2 Mb/s	~ 1 Mb/s	250 kb/s (2.4 GHz) 40 kb/s (915 MHz) 20 kb/s (868 MHz)	~ 100 Mbps	Tens of Mbps to several Gbps
Power Consumption	Very low	Very low	Low	Medium	Low	Medium	Low	Low for IR LEDs
Protocol	EPC Global Class 1 Generation 2	ISO/IEC 18092	N/A	IEEE 802.15.1	IEEE 802.15.4	IEEE 802.15.4	IEEE 802.15.3	IEEE 802.15.7
Network Topology	P2P	P2P	Star, P2P	Star, P2P	Star, P2P	Star, Tree, Mesh	Star, Mesh	P2P
Merit and Demerit	Low power consumption, Low data transfer rate, Short to medium transmission	Low power consumption, High security, Very short transmission range	Low power consumption, Customizable antennas, Low data transfer rate, Short transmission	High data rate, Broader range, High power consumption	Moderate data rate, Moderate range, Low power consumption	Low power consumption, Wide range, Large network, Lower data rate	Wide bandwidth, Low power consumption, High data rate	Wide bandwidth, High data rate, Low penetration through obstacles
Refs	[123]	[124–126]	[127, 128]	[129]	[123]	[130]	[131, 132]	[133]

of range, energy efficiency, data security, and bandwidth. Table 2 provides a comprehensive overview, outlining key parameters such as frequency band, working range, data rate, protocols, and more for commonly used wireless communication methods, including RFID, NFC, Bluetooth, Zigbee, Ultra-Wideband, and others (Table 2).

Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a spatial and orientation-dependent contactless and wireless communication technology. The form of data is transferred by inductive electromagnetic coupling of a transmitting antenna (reader) connected to an external power to a receiving antenna (tag). This setup supports the operation of wearable devices either by charging the battery or directly powering the system to be a battery-free device. RFID is categorized into three primary frequency bands: Low-Frequency (LF) ranging from 120 to 140 kHz, High-Frequency (HF) at 13.56 MHz, and Ultrahigh-Frequency (UHF) between 868 to 956 MHz [130]. In LF and HF systems, the RFID mainly utilizes magnetic resonant coupling, where the energy is transferred through a shared magnetic field between the RFID reader and the RFID tag. This mechanism is also referred to as inductive coupling. LF and HF systems typically work at shorter ranges of up to a few centimeters to one meter. However, UHF RFID and Microwave RFID systems usually operate with electromagnetic or radiative coupling, which allows for a longer range of communication up to 10–12 m. RFID tags can be divided into active, semi-active, and passive tags. Active tags are powered by a battery and can send signals continuously and over a relatively longer distance, while semi-active uses it to power the microchip but not to broadcast a signal. The passive tags don't have an internal power supply and receive power from the incoming radio waves from the reader [134].

RFID sensor technologies are broadly categorized into chip-based and chipless types. Chip-based RFID sensors incorporate an RFID chip integrated with an external sensor, modulating the backscattered signal by incorporating sensing materials on the antenna or its coupling area. While this method supports high coding, its broader application is often limited by the higher costs associated with chip integration. Chipless RFID technology represents a transformative advancement over traditional integrated circuit (IC) –based RFID tags, primarily addressing cost and environmental robustness concerns. Utilizing unique physical structures that produce distinct electromagnetic (EM) signatures, chipless RFID tags operate without electronic chips, significantly reducing production costs and complexity. Information is encoded directly into the EM response of the tag's passive architecture, either through time-domain reflectometry (TDR) or frequency-domain techniques. Inkjet-printed flexible RFID tag sensors using nanomaterials including multilayer graphene, carbon nanotubes, gold, silver, and copper nanoparticles mark a substantial advancement in RFID capabilities, detecting toxic gases for instance [135]. Furthermore, tailoring the dielectric property of the substrates or the electrical conductivity of the conductors induces the shift of the tag response, which makes chipless RFID ideal for sensing various external stimuli, such as humidity, temperature, and mechanical strain. A work introduced a novel cross-polar dual-layer chipless RFID tag utilizing a ladder-shaped resonator design for enhanced performance and compact size, suitable for direct attachment to human skin without performance loss. Their tag is designed with an integrated ground plane and employs frequency shift encoding on a circular tag to maximize the active area and coding efficiency. The tag's substrate is created using 3D-printed techniques with metallic resonator patterns screen-printed onto the surface, facilitating mass production at low costs. Simulation and on-skin testing confirm the tag's robustness and stability with a substantial improvement over traditional L-shaped and straight resonators by offering stronger cross-polar radar cross-section, third-order harmonics, and orientation insensitivity [135]. A chipless RFID humidity sensor utilizing a finite Artificial Impedance Surface (AIS) with three concentric loop resonators, provides distinct and high-quality resonance nulls in its electromagnetic response. The sensor is crafted using cost-effective inkjet printing on a metal-backed cardboard layer, with the resonances shifting up to 270 MHz in response to humidity changes from

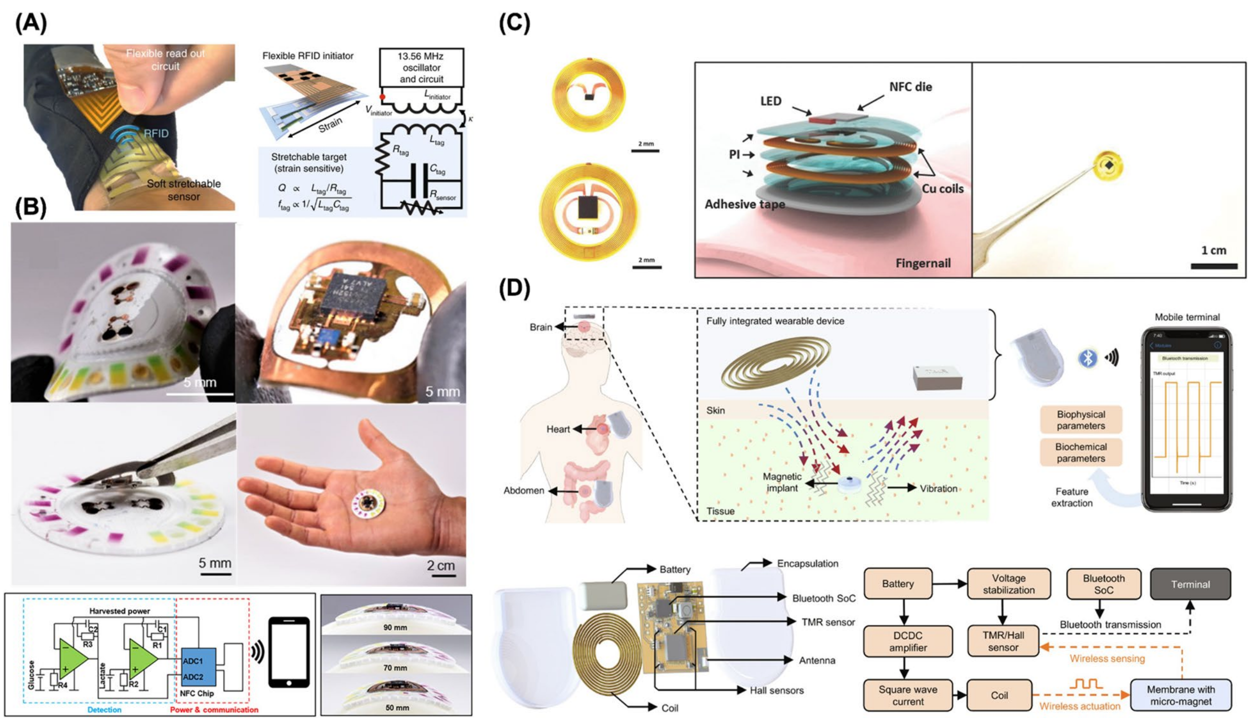

Fig. 4 **A** (Left) Photograph of the sensor on a human wrist to sense pulse. (Right) Simulations for the radiofrequency identification (RFID) system of a simplified circuit diagram. **B** Photographs and schematic illustration of electrochemical sensor readout showing a microfluidic patch with embedded sensors and battery-free NFC electronics. Image amplifying the reversible magnetic attachment of the NFC electronics to the microfluidic patch and a complete system on palm. **C** Schematic illustration and images of flexible millimeter-level NFC devices with and without LEDs and a picture of the device held at one edge by tweezers. **D** Schematic illustrations of the two-way wireless communication between the magnetic implant and the fully integrated wearable device with example illustration of data acquisition and processing in the mobile terminal. Enlarged schematic illustrations of the wearable device and a block diagram of the circuit of the fully integrated wearable device for wireless actuation and sensing

50 to 90% [136]. These innovative approaches lower the cost and enhance the sensitivity of RFID communication in varying environments, expanding potential applications in biosensing areas, where tags can detect changes in biological parameters by altering their EM response characteristics [137–139].

A wireless body area sensor network based on stretchable passive tags introduced a body area sensor network (bodyNET) that leverages RFID technology to seamlessly integrate chip-free and battery-free stretchable on-skin sensors with flexible readout circuits (Fig. 4A). This hybrid system is engineered for robust operation even under a 50% strain, highlighting its suitability for dynamic physiological monitoring with a favorable 20–25 mm vertical and lateral working range. The unconventional RFID design uses a detuned approach, where the sensors operate at a fixed frequency of 13.56 MHz, but can tolerate shifts in frequency due to strain, thereby preserving system functionality and reliability. Critical technical specifications include a target resonant frequency (ftag) that varies with operational strain, impacting the quality factor (Q) and coupling factor (κ) between the sensors and readout units. The system demonstrates high gain when the tag frequency is precisely 13.56 MHz or shifts above 25 MHz. This setup allows the RFID system to maintain high sensitivity (gain > 1 mV/Ω) to changes in sensor resistance, even under significant mechanical strain. The sensors and circuits are designed to maintain their functionality without the need for rigid components, facilitating continuous, real-time monitoring of vital signs like pulse and respiratory rates across various physical activities [140].

Near Field Communication (NFC)

Near Field Communication (NFC) operates by transmitting signals in the form of electromagnetic waves within the RF band, specifically at 13.56 MHz. This frequency falls within the HF band used in radio communications. NFC technology uses electromagnetic induction between two loop antennas—a reader and a tag—by relying on inductive coupling. This coupling involves a transmitting coil and a receiving coil, which work together to transfer information. The NFC system primarily utilizes non-radiative electromagnetic waves, and the signal transfer occurs within a proximity of approximately $\lambda/2\pi$ from the transmitter. One of the significant advantages of NFC is its insensitivity to obstacles between the communicating devices. Unlike other wireless communication technologies that may suffer from interference caused by physical barriers, NFC's inductive coupling allows seamless data transmission even in the presence of obstacles. The working range of NFC is notably short, typically within 4 to 10 cm. This limited range also ensures that NFC devices only interact with the intended target, reducing the risk of accidental or malicious connections. These characteristics make NFC reliable for applications where data confidentiality is the top concern.

Similar to that of RFID, there are three main categories of NFC tags: active NFC tags, passive NFC tags, and semi-passive NFC tags. The power required for NFC communication is relatively low compared to other wireless communication technologies. This efficiency is partly due to the short-range nature of NFC, which reduces the need for high transmission power. Passive NFC tags especially, those that do not have their own power source, draw the necessary energy from the electromagnetic field generated by the NFC reader, further minimizing power consumption. Data transfer speed in NFC technology varies depending on the mode of operation. NFC can operate in three different modes: reader/writer mode, peer-to-peer mode, and card emulation mode. In reader/writer mode, data transfer speeds can reach up to 424 kbps. In peer-to-peer mode, which allows two NFC-enabled devices to communicate directly, data rates are typically lower, around 106 kbps to 424 kbps. Card emulation mode, commonly used for contactless payments, operates at similar speeds, ensuring quick and efficient transactions.

In the pursuit of advancing wearable technology, smaller biosensors are increasingly favored due to their enhanced comfort, reduced physical impact, and improved integration with the human body. A miniaturized flexible electronic system with NFC communication capabilities exemplifies this trend by presenting highly compact, lightweight NFC-enabled systems. The coils are encapsulated in polyimide layers to minimize strain during bending. The NFC chips are thinned to less than 100 µmt to ensure their compactness. The devices feature coil diameters of 5.8 mm and 7.04 mm (Fig. 4B) retained their operational integrity when subjected to curvatures relevant to fingernail mounting, consistently maintaining resonance frequencies at approximately 14 MHz and Q factors around 15. They achieved stable communication at distances up to 20 mm from a standard smartphone's primary coil [141].

An innovative battery-free, skin-interfaced microfluidic-electronic system designed for the analysis of sweat took advantage of the miniscule NFC technologies. The NFC-enabled electronics are mounted via a robust magnetic attachment. The module in their design operates in a low-power mode and features a minimal component count, enhancing its compactness and efficiency (Fig. 4C). It comprises a dual-layer, copper-on-polyimide substrate, integrated with a microcontroller and a 14-bit ADC, compliant with ISO 15693 standards. The NFC module also incorporates an amplification scheme composed of a voltage follower design with a high-frequency filter that eliminates fluctuations introduced by the electric field of the primary NFC antenna. This configuration facilitates magnetic coupling with electrochemical sensors embedded in a disposable microfluidic substrate, ensuring robust data transmission even under mechanical deformation [142].

Magnetic resonant coupling

Magnetic resonant coupling is another technology that utilizes electromagnetic fields for wireless communication. During the process, the transmitter coil generates an oscillating magnetic field, which induces an electric current in the receiver coil with a corresponding change of the voltage across the load resistor. The data transmission channel is established after modulation. By selecting appropriate inductive (L) and capacitive (C) components, both the transmitter and receiver are tuned to the same resonant frequency which allows a more efficient energy transmission, and a greater distance compared to the non-resonant couplings. [143].

Magnetic resonant coupling for wireless power transfer to multiple small receivers was explored [144]. Resonance between the source and load coils was achieved using lumped capacitors, which maximize efficiency by tuning both coils to the same resonant frequency. It was demonstrated that more than 50% of the power supplied by the source could be delivered to a single receiver at resonance, emphasizing the importance of high-Q resonant coupling for efficient power transfer. This technology provides broad applications in the development of sensor networks, and microrobotics, while minimizing energy consumption at the same time.

The strength of the magnetic field at the receiver coil is determined by the magnetic permeability of the medium. Human tissues, such as muscle and skin, have magnetic permeability nearly identical to air. This similarity makes intra-body magnetic resonance communication independent of tissue type, which leads to further development and application of this technology. A recent paper introduced millimeter-scale magnetic implants paired with a fully integrated wearable device for biophysical and biochemical sensing purposes [145]. Magnetic resonant coupling serves a pivotal role in communicating between the brain implant and the wearable device. The implants (Fig. 4D Top) which consist of a micro-magnet, an elastic membrane, and biochemical-selective surface coatings, are actuated by a pulsed magnetic field generated by the wearable device. This actuation induces implant vibrations, creating a dynamic magnetic field that can be detected and analyzed by sensors in the wearable device. The wearable device (Fig. 4D Bottom) includes a copper coil for magnetic field generation, a tunnel magnetoresistance (TMR) sensor, Hall sensors, a Bluetooth System on Chip (SoC), and a rechargeable lithium-ion battery, all encapsulated in a soft layer. The cerebrospinal fluid (CSF) viscosity, intracranial pressure (ICP), and CSF glucose levels were measured in vivo rat models, which are critical for diagnosing and treating neurological conditions such as traumatic brain injury, stroke, and brain inflammation.

Another paper presents a novel biodegradable and flexible arterial-pulse sensor designed for wireless monitoring of blood flow [146]. This sensor employs fringe-field capacitive sensing and operates wirelessly through inductive coupling. It consists of a pressure-sensitive region and a bilayer coil structure for radio-frequency data transmission. The magnetic resonant coupling technology forms the backbone of the sensor's wireless operation. The system consists of an LCR resonator circuit, where the capacitive sensor is connected in series with an inductor coil. Changes in arterial diameter, caused by blood flow pulsations, are detected by the capacitive sensor. This results in a change in capacitance, which subsequently shifts the resonant frequency of the LCR circuit. Wireless data transmission is enabled through inductive coupling between the sensor's internal coil and an external reader coil. When the external reader coil generates a magnetic field, it induces a current in the sensor's coil if they are tuned to the same resonant frequency.

Bluetooth and Bluetooth Low Energy (BLE)

Bluetooth technology is a wireless communication standard that operates in the 2.4 GHz ISM (Industrial. Scientific, and Medical) band, which is a globally available frequency range. It operates over the IEEE 802.15.1 standard – a specification for wireless personal area networks (WPANs). Bluetooth uses the Frequency Hopping Spread Spectrum (FHSS) and divides the 2.4 GHz band into 79 channels [147]. Bluetooth technology significantly enhances the functionality of wearable biosensors, providing efficient, low-power, and secure wireless communication. It facilitates real-time data transmission from the sensor to mobile devices, enabling continuous monitoring of physiological parameters such as heart rate, blood oxygen levels, and glucose levels. This real-time data can be processed and analyzed on connected devices or sent to cloud services for further analysis. An integrated biosensor was designed to monitor cortisol levels in real time through sweat [148]. It utilizes a field-effect transistor (FET) array combined with a newly identified cortisol aptamer. The FETs, fabricated on flexible polyimide substrates, are integrated into a smartwatch, enabling seamless on-body monitoring (Fig. 5A). Bluetooth communication facilitates real-time data transfer to an Android smartphone application, providing a graphical user interface (GUI) for users to set operational modes, display data, and store it for long-term tracking. The application also integrates with Google Cloud Storage, ensuring the data is accessible and archived for further analysis.

BLE namely is designed for low power consumption. It extends the battery life of wearable devices and allows them to operate for extended periods without frequent recharging [130]. Similar to classic Bluetooth, BLE operates in the 2.4 GHz ISM frequency band. However, BLE differs

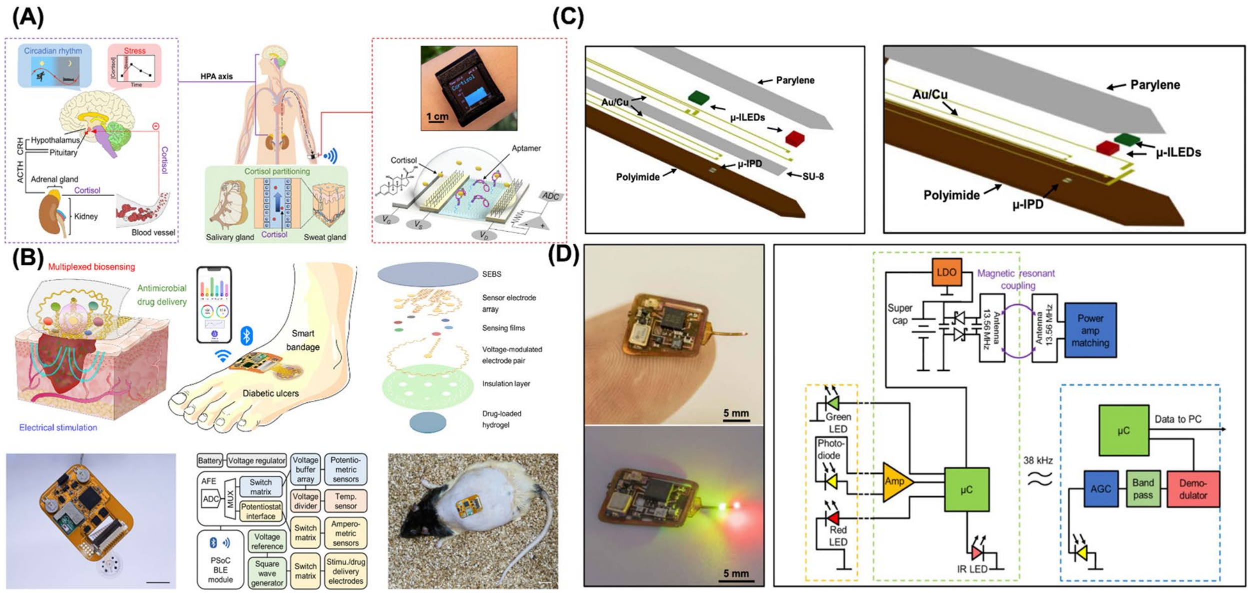

Fig. 5 An Illustration of noninvasive cortisol biomarker monitoring using a wearable aptamer-field-effect transistor sensing system. ACTH, adrenocorticotropic hormone; CRH, corticotropin-releasing hormone. **A** sensing system showing saliva and sweat samples analyzed by an aptamer-field-effect transistor (FET) with a photograph of an aptamer-FET-enabled biosensing smartwatch and a schematic illustration of cortisol sensing by an aptamer-FET sensor. **B** (Top) A schematic of a soft wearable patch on an infected chronic non-healing wound on a diabetic foot with layered assembly of the wearable patch, showing the soft and stretchable poly[styrene-b-(ethylene-co-butylene)-b-styrene] (SEBS) substrate, the custom-engineered electrochemical biosensor array, a pair of voltage-modulated electrodes for controlled drug release and electrical stimulation, and an anti-inflammatory and antimicrobial drug-loaded electroactive hydrogel layer. (Bottom) Schematic diagram and photograph of the fully integrated miniaturized wireless wearable patch with 1 cm scale bar. Photograph of a fully integrated wearable patch on a diabetic rat with an open wound with 2 cm scale bar, including ADC, analog front end (AFE); programmable system on chip (PSoC), multiplexer (MUX), BLE. **C** Schematic illustrations highlighting two representative filamentary designs: (Left) dual-layered design for deep brain rStO2 sensing of mice and (Right) single-layered design for highly localized rStO2 sensing in other tissue regions. **D** Photographs showing integrated wireless, battery-free oximeters in operation mode with illuminating m-ILEDs with a block diagram of the electrical working principles. LDO: low-dropout regulator; AGC: automatic gain control; Supercap: supercapacitor

in its channel structure, supporting only 40 channels compared to Bluetooth's 79 channel [149]. This reduction in the number of channels results in a shorter synchronization time, enhancing the efficiency and responsiveness of BLE communication. An article presents a stretchable wireless wearable bioelectronic system for multiplexed monitoring and treating infected chronic wounds [5]. The system leverages BLE for real-time wireless data transmission from the biosensors embedded in the wearable patch to external devices such as smartphones. (Fig. 5B Top) This enables continuous monitoring of wound biomarkers, including temperature, pH, ammonium, glucose, lactate, and uric acid. In vivo studies use a diabetic mouse model to demonstrate significant changes in wound fluid composition in response to infection and subsequent treatment. (Fig. 5B Bottom) Elevated levels of uric acid, temperature, pH, lactate, and ammonium are indicators of inflammatory and metabolic responses. The multifunctional capabilities of this bioelectronic system represent a substantial advancement in chronic wound management.

Zigbee (IEEE 802.15.4)

Zigbee is a wireless communication protocol that is designed for low-power, low-data-rate, and short-range applications. It operates based on the IEEE 802.15.4 standard. Zigbee uses direct sequence spread spectrum (DSSS) and operates in the 2.4 GHz, 915 MHz, and 868 MHz frequency bands. These bands offer different data rates like 250 KB/s (2400 MHz), 40 KB/s (915 MHz), and 20 KB/s (868 MHz).

Data transmission occurs through small packets. It achieved power efficiency by entering sleep modes when not in use, significantly reducing power consumption [150]. This makes Zigbee suitable for long-term battery-operated devices. Zigbee has a working range of 10–100 m. Each device in a Zigbee network, typically a router or coordinator, can directly connect to a maximum of 254 other devices due to its addressing scheme, enabling the formation of extensive networks. The hierarchical and mesh structure of Zigbee networks supports an overall network size of up to 65,535 nodes, leveraging a 16-bit addressing system that allows for this extensive scalability. The devices in the Zigbee network can be arranged as star, tree, and mesh topologies, providing high flexibility and ideal for industrial control and medical data collection [151, 152].

Optical communication

Optical communication, particularly leveraging infrared (IR) light, is a method for data transmission that offers significant advantages such as high bandwidth, low attenuation, and immunity to electromagnetic interference. Operating within the 700 nm to 1 mm wavelength range, IR optical communication is employed for short to moderate-distance data transfer. This system utilizes IR LEDs or laser diodes as transmitters and photodetectors as receivers, with data encoding achieved through modulation techniques such as pulse modulation. IR optical communication is extensively applied in various domains, including short-range data exchange between devices, and medical applications. Its high security is attributed to the narrow IR beam, which does not penetrate walls, thereby minimizing the risk of data leakage. Additionally, its immunity to electromagnetic interference makes it particularly suitable for environments with high electronic noise. In the medical field, IR communication is indispensable for non-invasive monitoring and implantable devices, facilitating real-time data transmission from within the body to external monitors [153]. IR communication remains a cost-effective, reliable, and interference-free solution. This technology's versatility is evident in its widespread use across consumer electronics and healthcare, underscoring its significance in modern communication systems.

A work featuring wireless, battery-free optoelectronic systems as subdermal implants for local tissue oximetry introduces an advanced device designed for continuous in vivo monitoring of tissue oxygenation [154]. This device integrates microscale optoelectronic components of m-ILEDs and m-IPDs, on a polyimide substrate for real-time sensing (Fig. 5C). It employs wireless power harvesting via magnetic resonant coupling and utilizes IR communication technology for data transmission. The IR communication block (Fig. 5D) features a 950 nm IR LED, operating at a carrier frequency of 38 kHz. The External photoreceivers are equipped with automatic gain control, band-pass filtering, and demodulation capabilities to receive the transmitted IR signals. These receivers convert the optical signals back into electrical signals for further processing. This setup allows for high data integrity and effective operation even when fully implanted subdermally. The system transmits data at rates exceeding 27 Hz with 12-bit resolution, ensuring accurate and continuous monitoring without physical tethers.

Ultra-Wideband (UWB) and acoustic

Ultra-Wideband (UWB) communication is a wireless technology that operates within the 3.1 to 10.6 GHz frequency band, utilizing narrow pulses of extremely short duration for data transmission. It is allocated with 7,500 MHz of spectrum by the Federal Communications Commission (FCC). UWB facilitates high data rates ranging from hundreds of Mbps to several Gbps with low power consumption, making it ideal for short-range applications. UWB offers high precision in ranging and localization, enhanced security due to its spread spectrum nature, and scalability to support a high density of devices. Its applications span from high-speed data transfer in personal area networks and portable devices to continuous health monitoring systems [154].

Wireless communication through acoustic or ultrasound in wearable devices leverages sound waves, typically in the ultrasound frequency range (above 20 kHz) to transmit data. This method is advantageous for its low power consumption, non-invasive nature, and ability to work in environments where traditional RF communication may face interference. The process involves a transmitter to convert electrical signals into ultrasonic waves using piezoelectric transducers, and a receiver to capture the ultrasonic waves and convert them back into electrical signals for data processing. This method offers several advantages, such as low power consumption and non-invasiveness, making it ideal for battery-operated wearables in patient monitors [155].

Applications overview

Wearable biosensors

Wearable sensors have become integral to modern healthcare, offering continuous, non-invasive monitoring of physiological signals. These compact, body-worn devices enable real-time health tracking, improving early detection and management of diseases. With advancements in technology, wearable sensors are increasingly being used in personalized healthcare, fitness monitoring, and chronic disease management [156–158].

Cardiac monitoring applications

Cardiology is one research area with heavy applications of wireless sensing platforms, applying this cutting-edge technology to provide continuous, remote real-time data on various physiological parameter [159], such as heart rate, electrocardiogram (ECG) signals, and blood pressure.

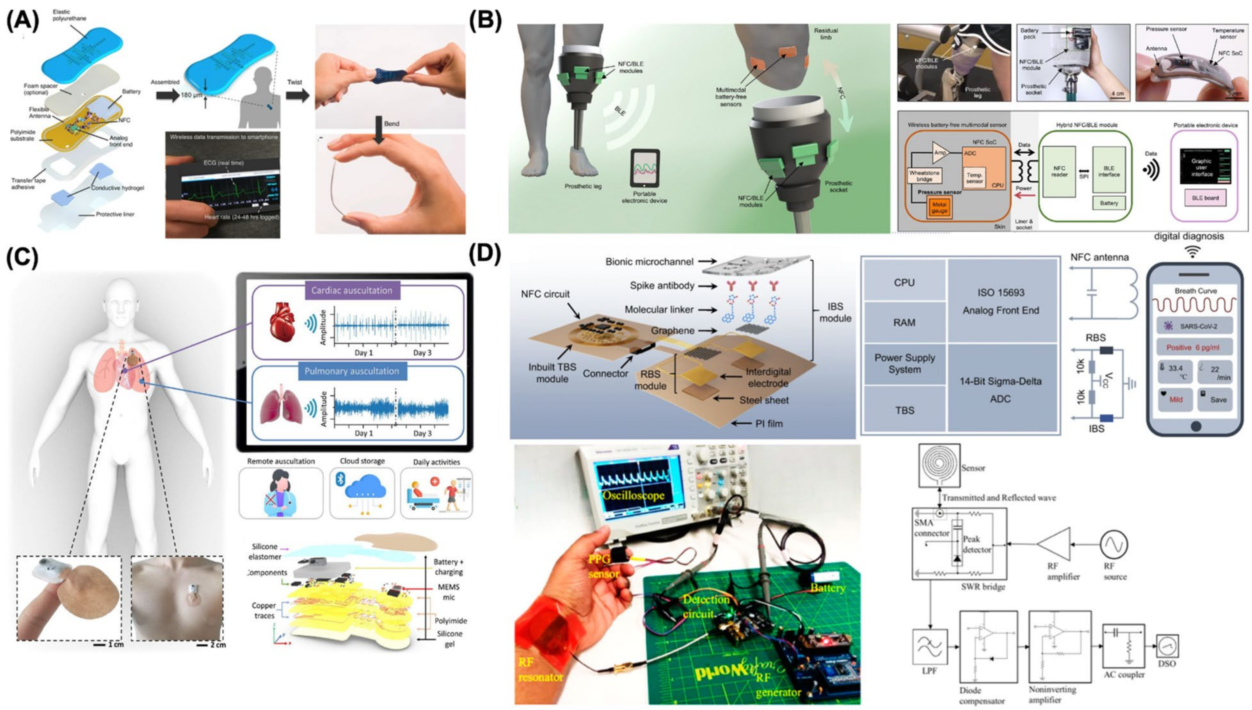

Fig. 6 **A** (Top) Diagram of soft flexible cardiac sensor with indications of electronic, adhesive and hydrogel layers. Data acquired by the device is wirelessly transmitted to a smartphone via NFC for visualizing logged heart rate data and real-time ECG waveforms. The smartphone then transmits this information to a cloud server using WIFI or cellular connectivity. (Bottom) Diagram of soft wearable stethoscope with remote monitoring schematics and real-time graphs of cardiac and pulmonary auscultation data (**B**) Diagram of skin-prostheses sensor interface in which wireless, battery-free multimodal sensors are imbedded on a residual limb with NFC/Bluetooth Low Energy (BLE) modules on the outer surface of a prosthetic socket (**C**) Diagram of pathogenic infection diagnosis system (PIDS) in which acquired health data can be transmitted through NFC-enabled smartphone (**D**) RF transmitter and modulated detection circuit system involved with recording mechanism of blood flow detection device

Heart rate / ECG patch One example of a cardiac monitoring application is a wearable smart patch with an advanced cardiac biosensor that is designed for the contiguous, remote monitoring of heart rate and ECG signals [160]. Characterized by its ultrathin profile and lightweight construction, the device contains multiple flexible polymeric, electronic, adhesive, and hydrogel layers, allowing for precise direct skin contact (Fig. 6A). A key component of the wearable patch's design is its dual NFC and BLE wireless communication system. Data communication via NFC, which enables short-range communication, provides real-time transmission of ECG and heart rate data to a smartphone or tablet when the device is in close proximity (approximately 3 cm) to the NFC-enabled reader. For longer-range communication, the device utilizes BLE, operating at 2.4 GHz. This capability allows the device to stream physiological data to consumer electronics and remote servers, providing continuous monitoring and logging without requiring direct, close-range interaction. The device's flexible PCB design incorporates a custom antenna that is optimized for both NFC and BLE communication. This antenna wraps around the circumference of the patch device, ensuring efficient operation in both free air and on soft tissue. The flexible antenna design is crucial for maintaining reliable connectivity across various smartphones, accommodating variations in NFC broadcast power. Additionally, the patch's power management system is designed to optimize energy usage and extend operational life. It includes a primary cell battery for backup power, but its main functionality—data logging and streaming—can be powered by NFC alone. The device features a microcontroller with integrated ADCs (Analog-to-Digital Converters) for precise signal conditioning and processing. Additionally, end-to-end encryption is employed to secure data transmission from the patch to the smartphone and subsequently to cloud servers.

Stethoscope A unique device designed for continuous, real-time cardiopulmonary auscultation using wireless sensing capabilities is a soft wearable stethoscope [161]. The integrated stethoscope system includes a microelectromechanical system (MEMS) microphone, a flexible thin-film circuit, a rechargeable battery, and a BLE unit for wireless data transmission. It features an elastomeric enclosure with a silicone gel backing for multiple uses and consistent sound detection (Fig. 6A). The flexible, soft design conforms closely to the skin and performs remote wireless monitoring without physical interaction between patients and physicians, addressing limitations of traditional and digital stethoscopes such as bulkiness, rigidity, and motion artifacts. The wireless capability of the SWS allows it to capture high-fidelity cardiopulmonary sounds and transmit them in real-time to a mobile application. This app is designed for recording, tracking, and displaying real-time signals, facilitating remote monitoring without the need for frequent hospital visits. The BLE unit streams data continuously, while a denoising algorithm filters out extraneous noise. Machine learning algorithms then classify various abnormalities, such as crackles, wheezes, stridor, and rhonchi. The wireless design ensures that the device can be used continuously for over 10 h on a single charge, making it ideal for remote patient monitoring and automated disease diagnosis.

Sensor-prosthesis interfaces

Prosthetics are another clinical sector in which wireless sensor technologies have been applied to—an instance of this is a novel soft, wireless physical sensor system to enhance the comfort and functionality of prosthetic sockets through a wearable platform [162]. This system integrates millimeter-scale pressure and temperature sensors into a flexible, battery-free platform that adheres to the skin-prosthesis interface (Fig. 6B). The thin pressure sensor consists of metal strain gauges in a 3D-framework to allow for precise pressure measurements. The sensors, which are imperceptible and non-invasive, continuously monitor pressure and temperature variations as the residual limb's volume changes during different activities. Data is wirelessly transmitted to a portable electronic device, such as a smartphone or tablet, through a reader module attached to the prosthetic socket. A design reminiscent of many other wireless sensing applications, this system uses a combination of NFC and BLE technologies, in which each battery-free sensor is paired with an NFC/BLE module mounted on the prosthetic socket's exterior. This module facilitates data transfer and powers the sensors through magnetic inductive coupling via NFC, while also enabling long-range data transmission to remote devices like smartphones and tablets using BLE. This dual wireless approach reduces the bulk and health risks associated with batteries, offers greater freedom of movement, and provides a significant improvement over previous NFC-only devices, especially in terms of monitoring and communication range. The system demonstrated accurate, real-time monitoring in both non-amputees using prosthesis simulators and individuals with transtibial and transfemoral amputations.

Electronic skin

An emerging area of wearable bioelectronics application is electronic skin, which are soft flexible patches that are used for precise diagnosis, monitoring, and treatment of various pathological conditions on the skin surface [163]. A study on electronic skins introduced a composite-based flexible and stretchable multifunctional electronics skin sensor utilizing MXene-Ti3C2Tx and 3,4-ethylene dioxythiophene (EDOT) deposited on laser-induced graphene sensor achieves high strain sensitivity (2,075), a temperature coefficient of resistance (TCR) of 0.86%, and low skin-contact impedance. Integrated into an ultrathin and resilient elastomer substrate, the sensor monitors strain, temperature, and ECG signals effectively. A key innovation is the integration of a flexible, low-power RF energy harvesting, battery-free NFC wireless patch system. This system, featuring a flexible antenna and surface-mounted electronic components, transmits strain data wirelessly to a smartphone. The wireless setup enables real-time detection of physiological health indicators and body-induced deformations, paving the way for advanced wearables in smart skin and healthcare applications.

Breath detection

To address the challenge of rapid non-invasive diagnosis of respiratory virus infections, researchers developed a wireless, battery-free, multifunctional pathogenic infection diagnosis system (PIDS) for diagnosing SARS-CoV-2 infection and symptom severity [164]. This system allows for blow and breath sample analysis within 110 s and 350 s, respectively. It enables simultaneous gaseous sample collection, biomarker identification, abnormal physical sign recording, and machine learning analysis. The diagnostic capabilities of this system are versatile, as it can be applied to various miniaturized wearable or portable electronic platforms—the PIDS system could be embedded in many wearable settings, such as through an inbuilt mask platform, watches, mini detection kit, blow tests, necklaces, etc. The biosensing mechanism utilizes graphene, known for its high conductivity and large surface area. Graphene's ability to adsorb and desorb aerosols makes it an effective respiration biosensor (RBS). Additionally, dissolved viruses are captured by spike antibodies modified on the activated graphene, functioning as an immuno-biosensor (IBS). The system also includes an NFC circuit component with an inbuilt temperature biosensor (TBS) to measure exhaled breath temperature (Fig. 6C).

Integration of the IBS, RBS, and TBS modules results in a complete wireless, battery-free multifunctional PIDS that monitors various signals of viral aerosols. The IBS and RBS serve as the front-end biosensing molecules, while the TBS functions as the backend. The PIDS transponder collects data and communicates it to smartphones via the I/IEC 15693 standard, which wirelessly powers the system through an electromagnetic field. The ADC converts biosensing information into digital signals. A microcontroller unit (MCU) with a 2 MHz central processing unit (CPU) controls the sampling rate and packages the collected data into NFC Data Exchange Format (NDEF), accessible by smartphones or other RF readers. Machine learning algorithms then evaluate infection presence and severity through breath analysis. More specifically, the RBS module is reliant on wireless transmission techniques. RBS operates based on the adsorption and desorption of aerosols on graphene, which alters the surface resistance. With a constant voltage applied, the output current of the RBS module increases and decreases periodically with the user's breath. This allows the RBS module to sensitively record respiratory characteristics during inhalation and exhalation. These collected signals are wirelessly transmitted to a mobile phone via NFC technology to be further processed. This wireless transmission is crucial for the seamless integration of biosensors with mobile devices, enabling real-time data analysis and monitoring without the need for physical connections. The use of NFC technology ensures efficient and reliable data transfer, enhancing the usability and convenience of the PIDS for continuous health monitoring.

Blood flow detection

Non-invasive wireless sensing capabilities are necessary for precise blood flow detection and hemodynamic patient settings. Mohammed et al. outlines the design of a flexible NFC RF biosensor designed for multisite arterial blood flow detection [165]. Built on a flexible polyimide substrate, the device is conformable to the body's variable geometry, which is crucial for accurate health monitoring at various anatomical locations. The sensor system includes a spiral resonator skin patch and a wearable transceiver (Fig. 6D). The resonator operates at a frequency of 34.5 ± 1.5 MHz and establishes strong capacitive coupling with layered dielectric tissues, allowing for noninvasive detection of hemodynamic events through impedance matching and electromagnetic field interactions. The transceiver consists of a direct digital synthesizer for RF carrier generation and a demodulator unit that includes a resistive bridge, envelope detector, filter, and amplifier. This configuration enables the detection of blood flow events, such as systolic upstroke, systolic peak, dicrotic notch, and diastolic downstroke, at multiple sites including the radial artery, thorax, carotid artery, and supraorbital locations. The flexible RF resonator operates at lower power levels compared to traditional systems, enhancing its suitability for wearable applications. The biosensor system demonstrates significant improvements over previous rigid and power-intensive designs by providing a compact, low-power solution that is capable of high-sensitivity detection of cardiovascular events. This makes it a promising tool for personalized medicine and point-of-care applications, offering a non-invasive, conformable biointerface. Other biointerfaces have also been utilized for purposes such as inflammation management. [124]

Implantable biosensors

Wireless implantable, ingestible, or digestible biosensors allow for rigorous biophysical and biochemical monitoring, enabling real-time closed-loop interventions through in vivo measurements and continuous physiological detection [166]. Several biomedical applications exist for implantable sensors, ranging from neurological to gastroenterological pathways [167].

Osseosurface electronics

One emerging application of implantable wireless sensors is osseosurface electronics, an implementation in which wireless sensing devices are implanted and adhered directly to bone surfaces [168]. These battery-free devices are equipped with multimodal capabilities, including sensors for real-time bone strain measurement, millikelvin resolution thermography, and optical stimulation. They operate wirelessly through energy harvesting and data transmission, eliminating the need for internal batteries. The devices are permanently bonded to the bone using calcium phosphate ceramic particles, demonstrating stable integration and functionality in deep tissue environments. The system features a hybrid integration of a flexible substrate with miniaturized components for analog and digital functions, enabling conformal attachment to the bone while maintaining stability and minimizing strain on the target sensing region. The device utilizes magnetic resonant coupling (13.56 MHz) for wireless, battery-free power harvesting through thick tissues up to 11.5 cm. The system operates using NFC-compatible hardware, featuring a compact NFC system-on-chip (4 mm $\times$ 4 mm) that integrates a microcontroller and transponder for operational control (Fig. 7A). The analog front-ends (AFE) for strain and temperature sensing are optimized for low power consumption and high sensitivity.

Capsule sensor

Wireless ingestible capsules equipped with biosensors represent an advanced approach to non-invasively monitor gut health [169]. These devices integrate electrochemical sensors to analyze gut fluids, offering a means to diagnose gastrointestinal diseases by capturing and transmitting

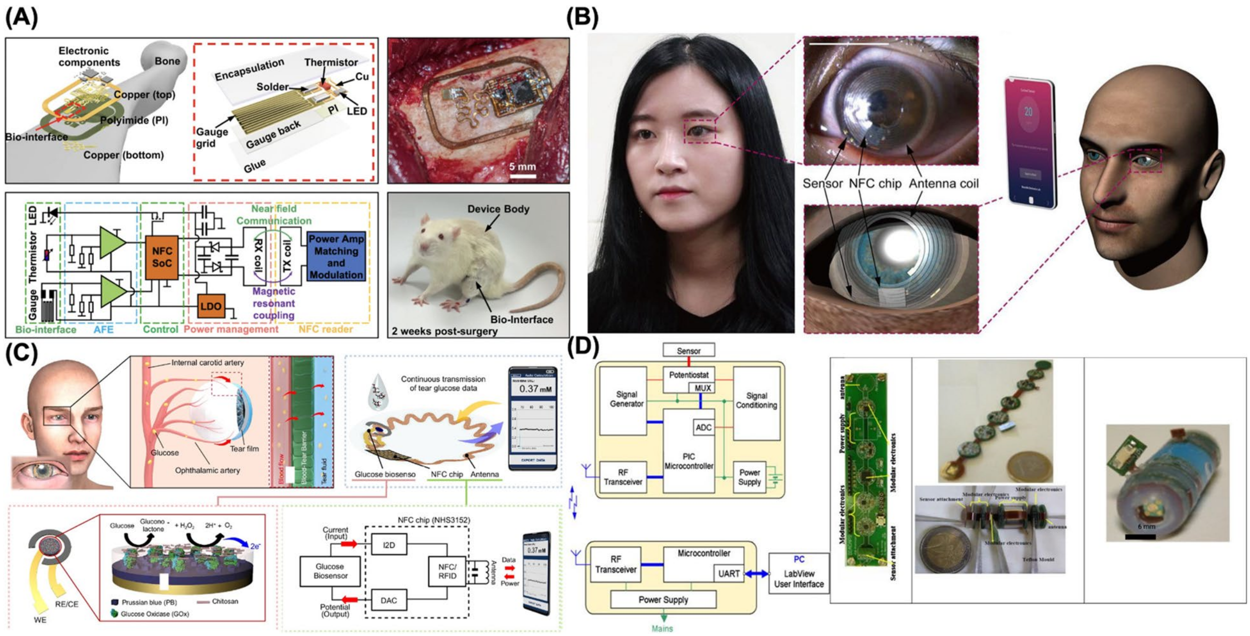

Fig. 7 **A** Diagram of osseosurface electronic interface, which includes an external NFC reader that supplies power and enables wireless communication. The implanted system features components for active power management, operational control, an analog front-end (AFE), and a biointerface. **B** Diagram of tear glucose (TG) monitoring system using the smart contact lens and wireless transmission of data through smart phone (**C**) Visual of smart contact lens with wireless cortisol immunosensing functionalities (**D**) Schematic of wireless swallowable capsule sensor with receiver module consisting of RF receiver, microcontroller, power supply and PC user interface

electrochemical data [170]. One such example is a novel wireless swallowable capsule designed for gastrointestinal (GI) tract investigation [171]. Unlike traditional endoscopy and colonoscopy, this capsule autonomously travels through the GI tract and utilizes a direct access, multi-electrode electronic tongue sensor to analyze gut fluids non-specifically. The sensor, integrated with a potentiostatic circuit, performs various voltammetric techniques, including cyclic, square wave, and differential pulse voltammetry. The capsule is powered by a lithium-ion cell and made from a polyimide flexible substrate encapsulated in polyether ether ketone (Fig. 7D). In order to integrate the wireless data transmission functionality, a compact RF transmission device operating at 433 MHz was selected for its ability to balance range and tissue penetration within strict size and power constraints. The device features very low power consumption in sleep mode and offers adjustable transmission power to accommodate different environments and distances. Though resulting in reduced radiation efficiency, the device uses a PCB stripline loop antenna, designed to fit within the capsule's size limitations. The capsule shows performance comparable to commercial laboratory equipment, as it is effective in electrochemically characterizing fecal waters, and represents a promising alternative to traditional GI diagnostic methods, offering a miniaturized, low-power tool for in vivo analysis and other biomedical applications.

Smart contact lenses

Another continuously advancing application of wireless sensing technology is biosensing through soft contact lenses. Due to its portable, non-invasive nature and direct-sample interface [172], these lenses can precisely measure various biomarkers in tears using integrated sensors with multiple modalities, and often use NFC technology to wirelessly transmit the data to mobile devices.

One such example developed by Ku et al. for immunosensing properties is a smart contact lens that monitors cortisol concentration in tears and allows for wireless remote control using a smartphone. Monitoring cortisol levels in body fluids poses significant challenges, including the instability of biologically active cortisol at room temperature and the need for bulky equipment for extraction and analysis, which limits mobility. The integration of biosensors with contact lens to analyze biomarkers in tears is particularly promising for this reason. Utilizing NFC technology, the cortisol-sensing lens, composed of a cortisol sensor and stretchable substrate interconnecting a system of wireless circuitry, enables battery-free operation by wirelessly receiving power and transmitting data with sufficient bandwidth (Fig. 7C). Unlike previous smart contact lenses, this system incorporates a stretchable NFC chip (NHS 3152, NXP Semiconductors), a transparent antenna, capacitor, resistor, and the cortisol sensor. The NFC technology operates in a passive communication mode, where an external mobile device generates a magnetic field to power the lens's LC circuit, enabling the NFC chip to read the cortisol sensor's resistance and transmit the data wirelessly. The circuit includes a digital-to-analog converter (DAC) to apply bias voltage and an ADC to read the sensor's resistance changes, facilitating real-time health monitoring [173].

Another wireless contact lens design focused on biomarker detection, designed for continuous monitoring of tear glucose levels, offers a non-invasive alternative to traditional blood glucose measurement. This lens quantitatively monitors tear glucose in basal tears, excluding the effects of reflex tears, and provides continuous data at sub-minute intervals. It features a glucose biosensor that detects changes in tear glucose, enabling precise estimation of the "personalized lag time" between tear and blood glucose. The lens's design, which includes soft, stretchable, and biocompatible materials, ensures comfortable wear and minimizes eye irritation. Similarly to the previously discussed cortisol sensor, this lens integrates an NFC chip for wireless data transmission, allowing seamless communication with a smartphone for real-time glucose monitoring. The smart contact lens leverages a stretchable and transparent antenna made from networks of silver nanofibers (AgNFs) and silver nanowires (AgNWs) to operate at the standardized NFC frequency of 13.56 MHz (Fig. 7B). Designed to fit the compact size of a contact lens, the antenna exhibits low sheet resistance and high transparency, essential for effective wireless communication and user comfort. The antenna is integrated with an NFC chip, capacitor, and resistor using stress-tunable hybrid geometries that combine rigid islands for device components and elastic joints for flexibility. This advanced contact lens platform addresses the limitations of conventional tear collection methods and provides continuous, reliable tear glucose measurements for effective diabetes management [174].

Multidimensional applications

Wireless sensing technologies allow for the multimodal implementation of health monitoring strategies. One such utilization is the simultaneous application of both wearable and implantable methodologies in the development of smart textiles. In tandem with the development of a fiber-shaped flexible capacitive strain sensor (FSFCSS), Zhang et al. employed the use of a printed RF coil in series to fabricate a wireless hemodynamic sensor. This system facilitates the acquisition of physiological signals and human–machine interactions within a wearable wireless sensing framework, forming a fully-integrated system [175].

The capacitive strain sensor, fabricated using direct ink writing technology, exhibits excellent dual-mode sensing performance, detecting both axial tensile strain and radial expansion strain. With high sensitivity, low-temperature operation, low power consumption, and dynamic and static response capabilities, the FSFCSS employs BTO@Ecoflex for its encapsulation and dielectric layer due to its superior dielectric properties and biocompatibility. Featuring a 3D parallel helical electrode structure, the FSFCSS effectively captures physiological signals like sound, respiration, heart rate, and pulse when attached to various body parts, making it ideal for non-invasive respiratory and cardiovascular disease prevention and diagnosis, as well as enhancing speech interaction. The system includes a portable data acquisition circuit board for multi-channel capacitance signals, ADC conversion, data preprocessing, and WIFI transmission.

The FSFCSS application in hemodynamic monitoring heavily leverages wireless technologies, with Zhang et al. proposing its use on artificial blood vessels to acquire hemodynamic information in real time, crucial for low-risk coronary artery disease treatment. To develop an implantable wireless hemodynamic sensor, FSFCSS was fabricated onto the surface of thermoplastic polyurethane (TPU) tubular fibers, processed with a single helical silver electrode as an RF coil. An LC circuit was formed by connecting the sensor in series with the printed RF coil; pulsatile changes in blood pressure induced expansion strain in the capacitive sensor, resulting in periodic capacitance variations. The resonant frequency of the LC circuit, through the RF inductor coil, converts these capacitance variations into a frequency shift phenomenon, enabling wireless measurement.

Performance tests demonstrated that the sensing system maintained clear spectral signals even with a wireless transmission distance of 3 cm. While interlayers between the transmitting and receiving coils could potentially attenuate the RF signal, research showed that simulated interlayers, including palms, Ecoflex film, and immersion in phosphate-buffered saline, had minimal impact on wireless signal transmission. This confirms the system's ability to monitor hemodynamic information wirelessly under implantation conditions. Further experiments indicated that the hemodynamic sensor effectively measured blood pressure and heart rate changes, with significant frequency shifts observed in the spectral signals across a blood pressure range of 0 to 200 mmHg. The resonance frequency decreased from 248.39 MHz to 228.89 MHz as blood pressure increased, and simulated pulse pressure changes at a heart rate of 60 bpm resulted in a peak frequency $\Delta f0$ of 1 Hz, matching the preset heart rate. These findings validate the sensor's capability to wirelessly monitor arterial pulse waves and hemodynamics accurately.

Conclusion and perspective

Wireless biosensors have revolutionized real-time health monitoring by offering unparalleled mobility and integration into daily life. This review explored the fundamental mechanisms of physical and chemical sensing, including thermal, piezoelectric, accelerometric, optical, electrochemical, and enzymatic technologies. Advanced wireless communication methods—such as RFID, NFC, Bluetooth, BLE, Zigbee, magnetic resonant coupling, and optical communication—enable seamless data transmission from sensors to monitoring devices. Innovative energy harvesting techniques, including RF methods (capacitive, inductive, and far-field coupling), acoustic energy via ultrasonic waves, biomechanical harvesting using triboelectric nanogenerators and magnetoelastic fibers, biochemical harvesting through lactate biofuel cells, and solar energy with flexible perovskite cells, ensure sustainable, battery-free operation.

The wide-ranging applications of wireless biosensors demonstrate their versatility. Wearable devices like smart patches and stethoscopes provide continuous ECG and cardiopulmonary monitoring. Prosthetic interfaces with integrated pressure and temperature sensors enhance comfort for amputees. Electronic skin enables multifunctional sensing—including strain, temperature, and bioelectrical signals—transmitted via flexible NFC systems. Breath detection systems use graphene-based sensors for rapid diagnosis of infections like SARS-CoV-2, transmitting data through NFC-enabled smartphones. Flexible RF biosensors offer non-invasive blood flow monitoring. In implantable and ingestible forms, osseosurface electronics adhere to bone surfaces for real-time strain measurements, powered by magnetic resonant coupling. Swallowable capsules with electrochemical sensors analyze gut fluids for gastrointestinal health, transmitting data via RF communication. Smart contact lenses monitor biomarkers like glucose and cortisol in tears, using stretchable antennas and NFC chips for data transmission. By integrating advanced sensing mechanisms, innovative energy harvesting, and wireless communication technologies, these biosensors enable continuous, real-time data acquisition essential for personalized medicine and point-of-care diagnostics.

Despite significant advancements, challenges such as distance limitations, signal instability, and electromagnetic interference remain. The top three challenges include long-term biocompatibility, ergonomics and motion artifacts, and power transfer efficiency. Improving the biocompatibility of biosensors is critical to preventing adverse reactions from the body. Recent progress in enhancing the biocompatibility of bio-related devices can be divided into categories such as – material selection, surface modification, self-solving, and self-healing properties. The use of soft, flexible polymers like polydimethylsiloxane (PDMS) or biodegradable materials such as poly(lactic-co-glycolic acid) (PLGA) helps align the mechanical properties of the biosensor with those of biological tissues [176, 177]. Biocompatible material Poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS) stands out due to its outstanding electrical properties [178]. Surface modification techniques, such as PEGylation—coating with polyethylene glycol or the functionalization of surfaces with bioactive molecules like RGD peptides can further mitigate immune responses and enhance cellular attachment, promoting better integration with tissues [179, 180]. Absorbable materials such as polylactic acid (PLA) and polyglycolic acid (PGA) that degrade into non-toxic byproducts are crucial to avoid the need for surgery removal [181]. There is a rising research focus on materials with self-healing properties that can repair themselves after mechanical damage, polymers with dynamic covalent bonds for instance could improve the longevity and durability of implants and wearables [182].

In addition to biocompatibility, user interaction with biosensors introduces additional design challenges, particularly in terms of attachment, adjustment, recharging, and disposal. The design of these devices must not only be intuitive but also seamlessly integrate into users' daily routines without requiring specialized tools or frequent maintenance. For instance, wearable devices for continuous monitoring should provide intuitive interfaces for recharging or battery replacement, minimizing disruptions in data collection and ensuring continuous monitoring. Self-sustaining energy solutions, such as energy harvesting or wireless charging, are being actively explored to eliminate the need for frequent manual interventions [183, 184]. Moreover, a significant challenge in the practical deployment of these devices is the management of motion artifacts caused by body movements and physiological activities [185]. Therefore, the development of accurate, user-centric, and practical designs, without compromising the functionality or durability of the biosensors, is essential for their successful adoption in real-time health monitoring [186].

Efficiently transferring a higher percentage of power from energy generation sites to wireless biosensors is crucial for their long-term and continuous operation. While various energy harvesting technologies convert ambient energy into electrical power, a significant challenge lies in minimizing losses during power transmission to the biosensors. Piezoelectric transducers harness mechanical stress from human motion; therefore, optimizing material properties and device architectures is essential to maximize the power delivered. Triboelectric nanogenerators (TENGs) utilize friction to generate charges for devices like sweat sensors [187]; enhancing surface interactions can increase power transfer efficiency. Radio Frequency (RF) energy harvesting captures electromagnetic waves through capacitive and inductive coupling, and improving antenna designs is vital to transfer a greater proportion of harvested energy to biosensors. For implantable biosensors, acoustic energy harvesting converts sound waves into power using piezoelectric transducers; refining acoustic coupling can enhance efficiency. Biochemical energy harvesting employs biofuel cells (BFCs) that convert metabolites like glucose and lactate into electrical energy [188–190]; advancements in enzyme activity and electrode materials are needed to increase the proportion of power delivered to biosensors. By focusing on improving power transfer efficiency from generation sites to devices, these technologies enable wireless biosensors to function more effectively, enhancing their practical utility in health monitoring applications.

Continuous exploration of novel materials and integration of artificial intelligence is expected to further enhance wireless performance and signal accuracy. In conclusion, the seamless integration of wireless biosensors within the Internet of Things (IoT) paradigm promises a new era of personalized, non-invasive, and continuous healthcare monitoring. The continued development of these technologies will play a crucial role in advancing medical diagnostics, treatment, and overall health management.

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Declarations

Competing interests The authors declare no conflict of interest.

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