Received 8 November 2024, accepted 30 November 2024, date of publication 11 December 2024, date of current version 23 December 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3515274

SURVEY

Biodegradable and Renewable Antennas for Green IoT Sensors: A Review

AMIR ZAHEDI[1], **(Graduate Student Member, IEEE),**
RANJITH LIYANAPATHIRANA[1], **(Life Senior Member, IEEE),**
AND KARTHICK THIYAGARAJAN[2], **(Senior Member, IEEE)**
[1]Infrastructure Health Monitoring Laboratory (IHM Lab), School of Engineering, Design and Built Environment, Western Sydney University, Sydney, NSW 2000, Australia
[2]Smart Sensing and Robotics Laboratory (SensR Lab), Centre for Advanced Manufacturing Technology, School of Engineering, Design and Built Environment, Western Sydney University, Kingswood, NSW 2747, Australia

Corresponding author: Karthick Thiyagarajan (K.Thiyagarajan@westernsydney.edu.au)

This work was supported by the Research Training Program (RTP) Postgraduate Research Scholarship Award provided by Australian Government Research Training Program and Western Sydney University.

ABSTRACT The development and integration of the Internet of Things (IoT) sensor technology across various domains have significantly transformed our work and daily lives, enriching society. However, the increase in the number of IoT devices leads to electronic waste (e-waste), which is a growing global concern. The continued development of sustainable IoT sensors utilizing biodegradable and renewable materials will not only help with reducing e-waste but also ensure wider adaptation of sensing applications thereby benefitting the global community. This review article examines the use of biodegradable and renewable materials in developing antennas for various sensing applications, emphasizing their sustainability, biodegradability, and recyclability. The main contributions of our work are six-fold. First, we review common bio-based materials used in microwave components, detailing the selection process for biodegradable and renewable materials, as well as their comparative advantages and limitations. Second, we examine biodegradable and renewable materials in antenna technologies for sensing applications, providing a comparative analysis based on microwave component type, material properties, dielectric constant, measurement method, relative permittivity, and relevant applications. Third, we analyze design requirements for antennas utilizing these materials, comparing antenna design type/technique, substrate and conductive materials, operating frequency band, size, and gain/directivity. Fourth, we evaluate antenna fabrication techniques, discussing their advantages and challenges. Fifth, we comprehensively review applications of biodegradable and renewable antennas in green IoT sensors, with focus areas including agriculture, environmental monitoring, healthcare, wearable electronics, logistics, and food processing. Finally, we address key research challenges, future prospects, and the potential of these technologies moving forward.

INDEX TERMS Sensor applications, IoT sensors, biodegradable sensors, renewable sensors, antennas, smart sensing, sustainability, advanced manufacturing.

I. INTRODUCTION

Technological progress, particularly in wireless communication networks, has significantly transformed our way of life, largely due to the integration of IoT sensors. These advancements enable seamless collaboration between physical and digital systems, allowing real-time data collection, analysis, and sharing across multiple domains. Antennas are essential in wireless communication systems, facilitating connectivity between IoT devices and enabling the transmission and reception of data over considerable distances [1], [2]. As a result, IoT sensors powered by microwave and millimeter wave antenna technologies are employed in various applications such as smart cities, smart homes, industrial automation, and

The associate editor coordinating the review of this manuscript and approving it for publication was Salvatore Surdo.

smart agriculture [3]. These sensors provide valuable environmental data, enabling more informed decision-making, optimized resource utilization, and minimized operational and maintenance costs. With the expansion of these networks, it is crucial to consider their impact on the environment and society, including concerns related to privacy, security, and sustainability [4]. Moreover, as new technologies continue to reshape our interactions with the world, it is essential to use them in a responsible and ethical manner [5], [6].

Proliferation of IoT sensors contributes to the generation of electronic waste (e-waste). Microwave devices, antennas, and other electronic components have limited lifespans and may become obsolete or be replaced by newer technologies, necessitating the disposal of outdated equipment. Improper disposal of e-waste can lead to environmental contamination and health risks due to the presence of hazardous substances.

Global annual e-waste generation is estimated to be in the millions of metric tons. For example, e-waste comprises a significant portion of Australia's overall waste, although the exact percentage may vary over time. In 2019, Australia's e-waste was approximately 521,000 metric tons, with an average annual generation of about 20.4 kg per person. According to [7], this figure is projected to reach 674,000 metric tons by 2030, corresponding to an average of 23.4 kg per person. Since then, factors such as technological advancements, consumer behavior, and recycling efforts may have influenced the rates of e-waste production, potentially altering these estimates. A significant portion of the weight of electronic printed circuit boards (PCBs) comes from the substrates. Replacing traditional, heavily polluting materials like FR4 epoxy glass laminates used in PCBs with environmentally friendly alternatives can significantly reduce the amount of harmful e-waste.

Eco-friendly materials include both recyclable materials, which can be reused when electronics reach the end of their life cycle, and biodegradable materials [8], which can naturally decompose without harming living organisms or the environment [9]. Commonly used environmentally friendly materials include paper [10], bioplastics such as polylactic acid (PLA), and organic conductors and semiconductors [11], [12]. Generally, these materials are not specifically designed for use in electronic devices and microwave components, leading to diverse electromagnetic characteristics. For example, PLA and similar polymers have low heat resistance, which limits the range of manufacturing methods and materials that can be used for circuit construction. Therefore, recent research needs to focus on implementing eco-friendly IoT devices to address these limitations by employing innovative designs and using green materials to enable new low-power sensing methods.

Green IoT (GIoT) involves the design and implementation of IoT systems aimed at minimizing their environmental impact. The main goals of GIoT are to significantly reduce CO_2 emissions and other harmful pollutants, protect the environment, and lower energy consumption in IoT devices. This is achieved by adopting energy-efficient methods in both

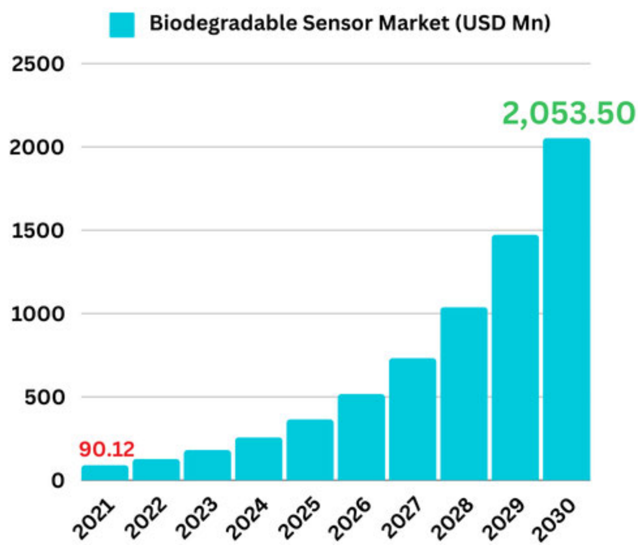


FIGURE 1. Projected revenue for the biodegradable sensor market by 2030 is expected to reach USD 2,053.50 million [13].

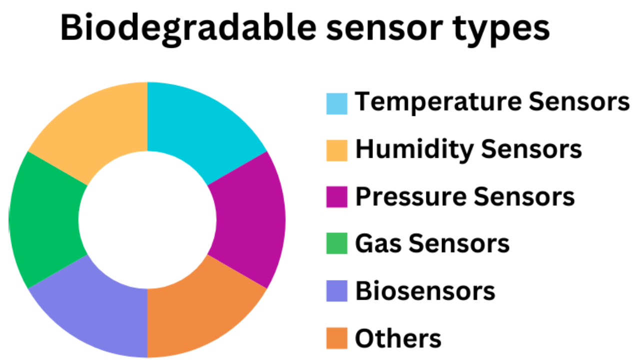


FIGURE 2. A pie chart illustrating the various types of biodegradable sensors available in the market [13].

hardware and software, which help lessen the greenhouse effect of current applications and the IoT itself. The entire lifecycle of Green IoT focuses on eco-friendly design, production, usage, and disposal/recycling to ensure a minimal environmental footprint [14].

Sustainable IoT prioritizes the use of eco-friendly materials and manufacturing techniques in the fabrication of IoT devices [4]. This approach includes incorporating biodegradable materials, recycled components, and non-toxic substances, all of which effectively mitigate the environmental impacts of device production and disposal, thereby reducing e-waste. Utilizing bio-based materials derived from renewable sources, such as agricultural waste or biodegradable polymers, can decrease reliance on conventional materials sourced from e-waste. This aligns with initiatives aimed at advancing sustainability and minimizing the environmental footprint of IoT technologies.

Biodegradable and renewable materials are crucial for developing sustainable and environmentally friendly

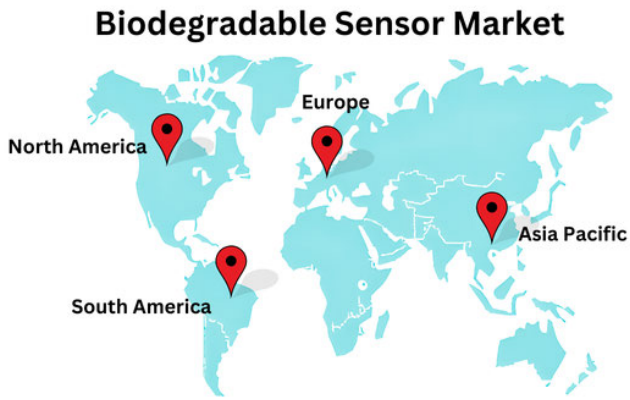


FIGURE 3. Global market growth of biodegradable sensors in different regions [13].

microwave technologies, especially in IoT sensor applications. These materials offer innovative solutions to minimize environmental damage, reduce resource consumption, and support the principles of a circular economy. Bio-based materials derived from renewable biomass sources, such as plants, algae, and agricultural residues, provide numerous advantages over traditional petroleum-based products [15]. Many bio-based materials are capable of biodegradation and composting, offering ecologically conscious disposal methods at the end of their lifespan. These benefits include a reduced carbon footprint and lower environmental impact throughout their entire lifecycle, from sourcing and manufacturing to disposal. Biodegradable and renewable materials significantly contribute to the development of environmentally friendly antennas, sensors, and devices that reduce greenhouse gas emissions, mitigate pollution, and conserve natural resources within the IoT framework.

To illustrate the growing impact and market potential of these technologies, consider Fig. 1, which shows the projected revenue for the biodegradable sensor market by 2030. The biodegradable sensor market is set for significant growth, with estimates indicating it will reach USD 2,053 million by 2030. This substantial increase is underscored by a notable compound annual growth rate (CAGR) of 41.8%, reflecting the market's vast potential and promising future [13]. As sustainability becomes increasingly important across industries, biodegradable sensors are emerging as a key technological innovation, offering eco-friendly solutions without compromising performance. Fig. 2 illustrates the different types of biodegradable sensors available in the market. Moreover, Fig. 3 shows the market distribution of biodegradable sensors across North America, Europe, Asia-Pacific, and other regions. It highlights the projected revenue trends from 2021 to 2030, indicating the growth and market potential in different geographical areas [13].

This review paper aims to provide a detailed overview of biodegradable and renewable antennas and their applications in green IoT sensors. It focuses on reviewing and comparing the state-of-the-art antennas made from biodegradable and renewable materials. The study discusses the current challenges in designing, processing, and integrating these materials into microwave devices such as antennas. Additionally, this review introduces and describes possible antenna fabrication techniques for practical use, envisioning the future of green IoT technology and sensing applications research.

The organization of the paper is illustrated in Fig. 4. Section II presents a detailed analysis of biodegradable and renewable materials commonly used in microwave components and antennas in particular. Section III focuses on the specific applications of these materials in antenna technologies, including various techniques for material preparation and characterization. Section IV examines manufacturing methods for biodegradable and renewable antennas, with an emphasis on integrating biodegradable materials into substrates and conductive components. Section V explores the use of biodegradable and renewable antennas in green IoT sensors, discussing potential future R&D opportunities and challenges in this emerging field. Finally, Section VI synthesizes the significant findings and offers insights into the potential impact of biodegradable antennas on creating environmentally friendly IoT sensors leading to reduced e-waste.

II. BIODEGRADABLE AND RENEWABLE MATERIALS

Microwave technology and advanced manufacturing are rapidly advancing, with a growing emphasis on sustainability and environmental friendliness in product development. However, achieving the necessary electrical and magnetic properties in bio-based materials for effective microwave applications poses significant challenges. These materials often lack adequate conductivity and magnetic interaction compared to synthetic counterparts. Additionally, their non-uniform characteristics and moisture content can affect performance in microwave systems.

To address these issues, researchers are exploring ways to tailor the electromagnetic properties of bio-based materials by blending them with synthetic counterparts during manufacturing. This approach creates novel materials that are both bio-based and capable of meeting the rigorous electromagnetic demands of microwave technology. When assessing or modifying bio-based materials for microwave use, careful attention must be paid to ensure their mechanical properties and degradation behavior align with environmental conditions. Despite these challenges, integrating bio-based materials into microwave technology shows great potential for advancing sustainability goals in the field.

A. COMMON TYPES OF BIO-BASED MATERIALS USED IN MICROWAVE COMPONENTS

In recent years, there has been increasing interest in using bio-based materials in microwave technology. These materials can be categorized into two main types based on their intended use: biodegradable materials and bioresorbable materials, which include bio-implantable types. Biodegradable materials break down into smaller, non-toxic

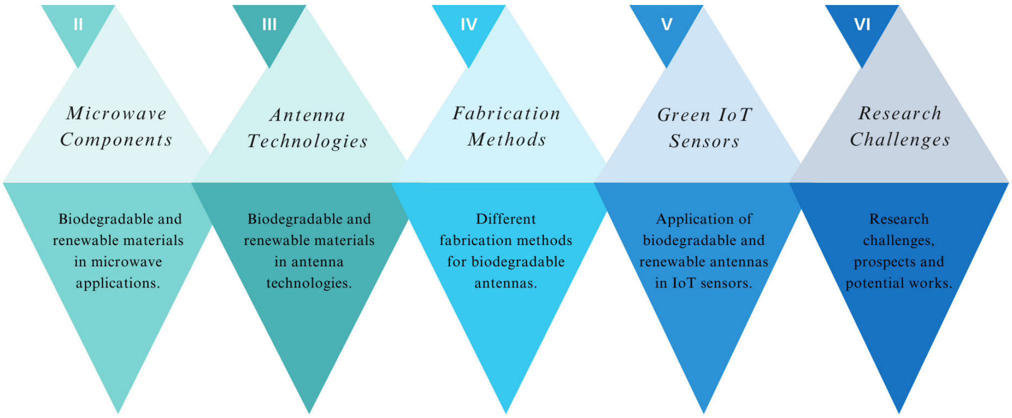


FIGURE 4. Organization of the review proposed in this article.

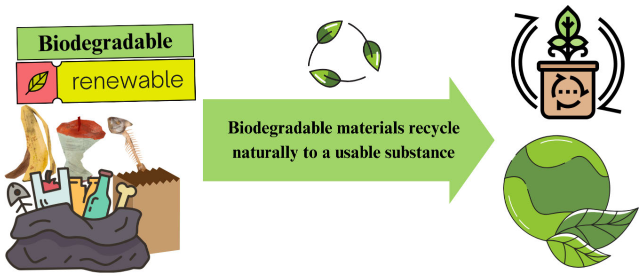


FIGURE 5. This picture illustrates how materials classified as biodegradable can decompose into harmless components through the action of microbes or environmental factors.

components and eventually return to the environment. Bioresorbable materials, designed to degrade safely within the body, offer mechanical reinforcement for real-time applications, including capsule endoscopy and tumor therapy. Bio-implantable materials, which are biocompatible and do not cause adverse effects when in direct contact with tissues, are suitable for various biomedical applications. It is crucial to seamlessly integrate these materials into microwave components and devices to ensure their effectiveness matches that of traditional microwave technologies.

Microwave technology is increasingly exploring the potential applications of biodegradable materials. Polylactic acid (PLA), derived entirely from renewable resources such as corn starch or sugarcane, decomposes readily and is commonly used in packaging, disposable tableware, and biomedical implants because it breaks down into non-toxic components in composting environments [16], [17], [18]. In contrast, materials like polyethylene (PE) and polyethylene terephthalate (PET) do not share the same biodegradability [19].

Polycaprolactone (PCL), another biodegradable polyester synthesized from renewable resources like castor oil, is frequently used in medical implants, drug delivery systems, and tissue engineering applications due to its slow degradation within the body [20], [21], [22], [23]. Additionally, polyhydroxyalkanoates (PHA), a family of biodegradable polymers produced by microorganisms, are fully biodegradable and find applications in packaging, agriculture, and biomedical fields [24], [25]. Starch-based biodegradable polymers, such as thermoplastic starch (TPS), are sourced from biological origins and are used in packaging, food containers, and agricultural mulches, where they naturally decompose in composting facilities or soil environments [26], [27], [28].

Fig. 5 illustrates how biodegradable materials break down into harmless components when exposed to microbes or environmental factors [29]. This visual representation highlights the transformative nature of biodegradable materials, emphasizing their ability to decompose naturally and contribute to environmental sustainability. These materials have the potential to be incorporated with IoT sensors operating in the microwave frequency bands.

On the other hand, microwave components are increasingly incorporating bioresorbable and bio-implantable materials, which hold great potential in various biomedical fields [30], [31], [32]. To effectively integrate these materials into microwave devices, it is crucial to consider not only their electromagnetic but also their biological properties to ensure compatibility with the human body. Materials such as PLA, PCL, PHA, and starch-based polymers offer a unique advantage: they can naturally degrade within the body over time. Their biodegradability and renewable sourcing make them ideal for applications such as orthopedic implants [33], [34], drug delivery systems [35], and tissue engineering [36]. Using these materials in microwave components for biomedical applications provides several benefits. They offer essential support for real-time tasks such as capsule endoscopy [37], tumor treatment [38], and detecting harmful bacteria [39]. Additionally, they reduce the need for multiple surgeries, enhancing patient safety and comfort. Furthermore, the slow degradation rates of materials like PLA and PCL ensure the long-term stability and effectiveness of medical implants and devices.

This paper primarily focuses on the first category of bio-based materials: biodegradable materials that can naturally

TABLE 1. Biodegradable and renewable material selection process and their comparative advantages and limitations.

Ref.	Material Type	Material Category	Performance	Scalability	Biodegradability /Recyclability	Advantage	Limitation
[40]	Bamboo	Natural Fiber	High structural strength	✓	✓	Rapid growth	Susceptibility to pests
[41]	Cork		Lightweight durability	✓	✓	Natural insulation	Cost variability
[42]	Jute		High tensile strength	✓	✓	Flexible and cost-effective	Limited durability
[43]	Rice Husk		Impact resistance	✓	✓	Abundant	Moisture absorption
[44]	Paper	Cellulosic material	Ease of processing	✓	✓	Versatile applications	Moisture-sensitive
[45]	PLA	Biopolymer	Good printability	✓	✓	Versatile applications	Heat-sensitive
[24]	PHA		Mechanical flexibility	✓	✓	Thermal stability	Higher production costs
[32]	PLA-SCS Biocomposite		Improved flexibility	✓	✓	Combined benefits of PLA and natural fibers	More expensive than standard PLA
[46]	BioFila Silk		Breathable comfort	✓	✓	Silk-like texture	Limited supply
[47]	Starch-based Polymer		Easy to mold and shape	✓	✓	Resource efficiency	Moisture-sensitive
[48]	Wood-fill PLA	Biocomposite	Lightweight construction	✓	✓	Natural appearance and texture due to the wood fibers	Lower mechanical strength compared to pure PLA
[49]	Graphene	Carbon-based	High strength-to-weight ratio	✗	✓	Highly conformal with high conductivity	High production cost
[50]	Tencel Fabric	Regenerated Fiber	High due to soft resilience	✓	✓	Resilient	High cost compared to traditional fabrics
[51]	Recycled Polyolefin	Synthetic Polymer	Versatile reusability	✓	✓	Waste-reducing	Quality variability

decompose without harming living organisms or the environment, and recyclable materials that can be reused when electronic devices reach the end of their life cycle.

Table 1 lists biodegradable and renewable material selection processes along with their comparative advantages and limitations. The table evaluates key performance metrics, scalability, and biodegradability or recyclability of materials. These materials are categorized by type, such as biopolymers, bio-based composites, and natural fibers. This comparison table provides valuable insights into the materials' suitability for the development of biodegradable and renewable antennas by outlining their primary advantages and limitations and emphasizing the trade-offs that must be considered in the context of sustainable technology.

B. APPLICATION OF BIODEGRADABLE AND RENEWABLE MATERIALS IN DIFFERENT MICROWAVE COMPONENTS

Recent advances in microwave technology have significantly expanded the applications of microwave sensors across various sectors, including healthcare, telecommunication, and environmental monitoring. These advancements have led to breakthroughs in areas such as Electromagnetic Interference (EMI) mitigation, shielding, and absorption. Radio Frequency Identification (RFID) technology, Wireless Sensor Networks (WSNs), Wireless Power Transmission (WPT), Radio Frequency Energy Harvesting (RF EH) [52], as well as smart textiles and wearable systems [53] have also seen rapid developments (see Fig. 6). As researchers investigate deeper into these fields, there is a growing interest in exploring the potential of integrating biodegradable materials into microwave-based sensing technologies to improve sustainability and functionality.

With advancements in material science and innovative processes, there is a growing emphasis on developing sustainable and eco-friendly EM shielding solutions to meet evolving technological needs. To mitigate EMI in communication systems and sensor nodes, shielding materials are crucial, limiting electromagnetic pollution. Modern microwave devices necessitate lightweight, flexible, and chemically resistant shielding materials, which conventional metals often cannot meet. Instead, research efforts are focused on developing materials that can absorb and convert EM waves into thermal energy, with bio-based renewable materials and their polymer composites emerging as promising candidates [54]. Various natural and synthetic materials, including cotton, bamboo, banana leaves, and agricultural waste, exhibit promising microwave absorption properties. Moreover, conductive polymers and nanocomposites are explored for their effectiveness in EM shielding, offering tunable conductivity, lightweight, and adhesiveness [55], [56].

Biodegradable flexible substrates offer a sustainable alternative for reducing the usage of toxic materials in high-speed communication systems. Wood, paper, fabric, and cardboard are examples of renewable alternatives that, when combined with substrate printing technologies, can be employed in the packaging and construction industries. In WSNs, wireless systems with biodegradable tiles have been developed for indoor smart floors, utilizing cork material to incorporate electronic components on the same antenna tile [41]. Additionally, biodegradable materials are employed in microwave sensors and front-end telecommunication systems, where mixer circuits are developed on paper substrates to mitigate potential environmental hazards [57].

In RFID applications, biodegradable materials are increasingly utilized for sensor integration. This integration can lead to cost reduction, convenient disposal, real-time tracking [58], environmental and food monitoring [59], and infrastructure health monitoring [60]. Broadband antennas

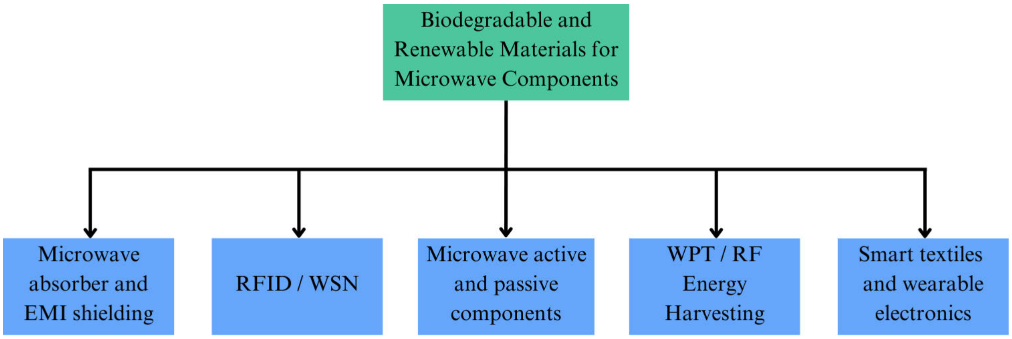


FIGURE 6. Biodegradable and renewable materials for microwave applications.

using organic conductive polymer materials have been engineered for ultra-high-frequency (UHF) RFID biosensor applications [61]. RFID tags and recyclable sensors on cellulose-based substrates demonstrate short read distances suitable for contactless technology devices [62]. Wireless sensors utilizing paper substrates can be integrated into RFID tags through printed electronics technology [63], enabling applications such as object identification, localization [64], and environmental sensing [65]. Additionally, highly flexible and readily disposable graphene RFID tags can be used for short-range communication [66].

The use of biodegradable materials in active and passive microwave components is also a significant step forward in developing green RF electronics. These materials, particularly graphene-based conductive materials, are gaining attention for their versatility in various applications. For instance, graphene has proven useful in creating low-noise amplifiers, frequency mixers, and microwave transistors, which are essential for improving wireless receiver circuits [67]. Moreover, graphene-based digital phase shifters offer stability and high-speed performance, making them attractive alternatives to traditional phase shifters [68]. Microwave diodes made from graphene also exhibit high-speed operation, making them suitable for RF applications [69]. Cellulose nanofibril (CNF) substrates derived from wood have been utilized for manufacturing RF passives and low-density digital logic circuits [70].

While only a few researchers have studied graphene-based materials, another application of biodegradable materials lies in RF energy harvesting and wireless power transmission components, offering an eco-friendly solution for powering battery-free sensors and extending their lifespan. By converting RF energy into direct current voltage through rectennas (rectifier + antennas), these sensors can operate without batteries, thus reducing environmental impact [71]. Recent developments include the use of biodegradable substrates, such as leather, jute fiber, and paper, to fabricate rectenna systems for wireless power transmission. Natural biopolymer materials, such as cellulose and palm tree remnants, are increasingly utilized as substrate materials for rectennas and other electronic components in RF energy harvesting systems. These materials offer sustainable alternatives and can support the fabrication of rectenna arrays and Schottky diodes directly on their surfaces. For instance, cellulose-based rectennas coated with PEDOT:PSS polymers are able to efficiently convert microwave energy into electrical charges [72]. A microstrip patch antenna successfully operating at 2.45 GHz for WPT is fabricated using natural jute fiber material in [73]. GaAs diodes were enclosed in CNF packaging, showcasing environmentally friendly RF energy harvesters [70]. Additionally, palm tree remnants are used to create RF energy harvesters with nanoparticle composites for microstrip patch antenna fabrication [74]. Metamaterial structures are printed on these substrates using conductive silver ink to enhance their performance. Moreover, recent advancements include the development of bioresorbable wireless power transmission systems using materials like polylactic glycolic acid (PLGA) for antennas, enabling potential applications in bioresorbable wireless implants [75]. These innovations mark significant progress in the field of eco-friendly electronics and lead to future developments in sustainable RF EH and WPT applications.

The increasing demand for smart textiles and wearable electronics arises from the trend of wireless device miniaturization and the widespread adoption of smart sensors. Textile materials are essential for seamlessly integrating wearable applications into the design process of garments. Notably, many wearable devices utilize biodegradable materials to ensure compatibility with the human skin and promote environmental sustainability. When selecting substrate materials for wearables, factors such as mechanical properties like flexibility, stretchability, durability, and adaptability to various shapes are critical considerations [54]. Additionally, lightweight, and easily manufacturable materials contribute to efficient mass production. Paper has emerged as a particularly promising material due to its extensive availability, particularly in applications like human motion detection and telemedicine. Polymers are frequently employed to enhance the flexibility of wearable materials [54]. In the field of microwave imaging, wearable bras constructed from organic materials operate at ultra-wideband frequencies for early-stage cancer detection, emphasizing single-use

TABLE 2. Biodegradable and renewable materials for microwave components.

Ref.	Microwave Component	Biodegradable/Renewable Material	Dielectric Constant Measurement Method	Relative Permittivity (ϵ_r)	Application
[32]	Sensor/Antenna	PLA-SCS biocomposite	Dielectric probe	PLA: 1, SCS: 3.4	Healthcare
[41]	Antenna	Cork	Resonator technique	1.237	Smart Floors and Smart Home
[42]	Rectifier	Jute	Not Given	1.64–1.8	WPT
[43]	Antenna & frequency selective absorber	Rice husk	Open-ended coaxial probe (OCP)	~2.43	5G radio
[44]	Variable attenuator and nested antennas	Paper	π resistive network	3.2	RFID Sensor
[45]	Antenna	PLA	Coaxial transmission line and probe	2.533, 2.473	WSN
[46]	Microwave ring resonator	BioFila silk	Dielectric probe	2.2432	Microwave passive sensors
[48]	Antenna	Wood-fill PLA	Dielectric probe	2.4	Wireless communication systems
[49]	Antenna	Graphene	Split cylinder resonator	3.5	Conformal & flexible electronics
[50]	Antenna	Tencel fabric	Microstrip line and T-resonator	2.36	IoT
[51]	Antenna	Recycled Polyolefin	Resonant method	2.375	RFID
[62]	Frequency doubler	Paper	Not Given	3.2	RFID
[78]	Harmonic transponder	Paper	Load pull methodology	2.55	IoT
[79]	Rectenna	PLA	Transmission line	2.7–2.9	RF EH
[80]	Rectenna	PLA	Not Given	2.57	WSN/IoT
[81]	Antenna	Wood-based PLA	Dielectric probe	2.4	Wireless communication systems

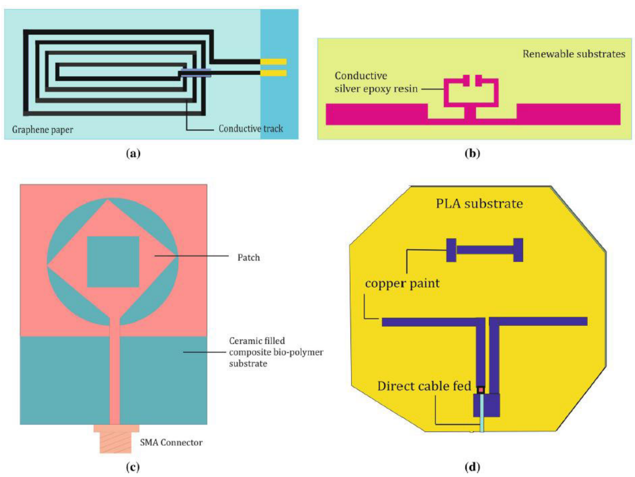


FIGURE 7. Microwave devices using sustainable materials include: (a) a flexible RFID tag made from graphene, (b) UHF RFID tags embedded on renewable materials, (c) a microstrip patch antenna created on a custom biopolymer substrate, and (d) a Yagi-Uda antenna mounted on a PLA substrate [54].

disposal [76]. Future advancements are anticipated with flexible graphene film-based sensors for human motion detection [77]. Throughout the wearable device design process, minimizing body coupling remains essential for optimizing performance and enhancing user comfort. Fig. 7 demonstrates the application of different environmentally friendly materials in different microwave components such as antennas and RFID tags [54].

In Table 2 a list of different microwave components made of biodegradable and renewable materials is given, along with their applications and the method of dielectric property measurement. PLA and cellulose-based materials such as paper and jute are some examples of biodegradable and renewable materials that are used in various microwave components. In the next section, we review materials especially suitable for antennas.

III. BIODEGRADABLE AND RENEWABLE MATERIALS IN ANTENNA TECHNOLOGIES FOR SENSING PURPOSES

Antennas are essential elements in wireless communication systems, facilitating the transmission and reception of electromagnetic signals across many applications. Because of their adaptability, they are capable of operating efficiently across a broad spectrum of frequencies, facilitating communication over short to long distances. Whether used in cellular networks, IoT devices, RFID systems, WSNs, or integrated into smart fabrics and wearables, antennas play a crucial role in enabling connectivity and facilitating data communication.

The use of biodegradable and renewable materials in antenna technologies is a relatively new area of research but holds promise for various applications, particularly in environmentally sensitive or disposable settings. Traditional antennas, commonly employed in IoT devices, particularly those used in outdoor or remote environments, contribute to the buildup of e-waste once they reach the end of their operational lifecycle. Biodegradable and renewable antennas present a sustainable solution, gradually breaking down into natural components and mitigating the environmental impact associated with e-waste disposal. Typically crafted from organic or eco-friendly carbon-based materials, these antennas naturally degrade over time when exposed to environmental factors like moisture, sunlight, and as a result of microbial activity.

Materials used in biodegradable and renewable antennas include biopolymers, bio-based composites, bio-waste, or natural fibers sourced from renewable origins [82], [83], [84]. Renewable materials enhance sustainability by allowing for reuse or recycling at the end of their life cycle, thereby reducing the need for new raw materials and minimizing waste. By incorporating both biodegradable and renewable materials, antenna technologies can significantly reduce their environmental footprint while maintaining performance standards. Fig. 8 presents the procedure for designing biodegradable and renewable antennas, starting from material selection to antenna fabrication and application.

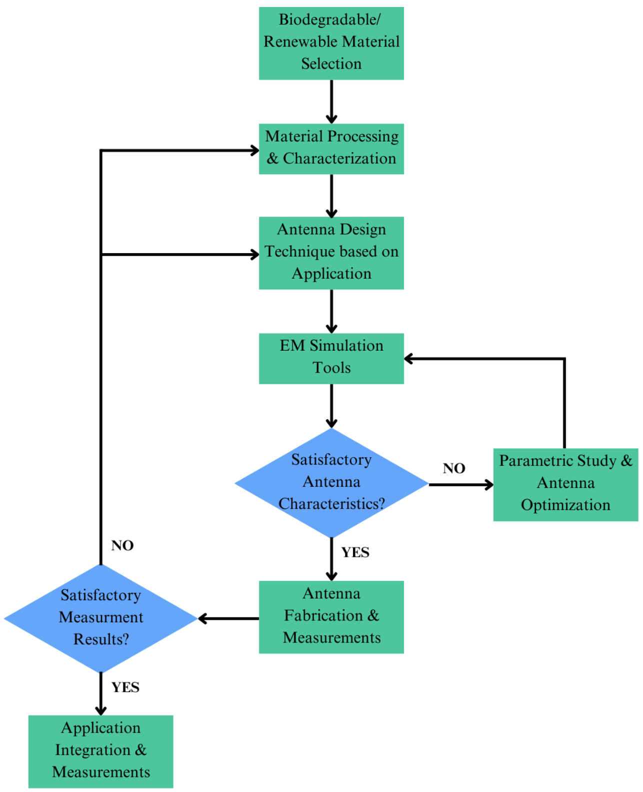


FIGURE 8. Biodegradable and renewable antenna design and fabrication procedure.

The first step in antenna design entails selecting the appropriate biodegradable and renewable material based on application requirements and material properties. In the case of microstrip antennas, biodegradable materials, such as jute [85], biopolymers like PLA [79], cork [58], or PHA [86], [87], offer promising alternatives for antenna substrates and conductive components due to their eco-friendly nature and potential for sustainable design [88]. The selection process requires careful consideration of factors like biocompatibility, mechanical strength, and dielectric properties, which are assessed using various evaluation techniques, including spectroscopy, microscopy, thermal analysis, and mechanical testing. The following section considers properties critical for determining the suitability of materials for use in antenna applications.

A. BIODEGRADABLE AND RENEWABLE MATERIAL PROPERTIES

When selecting materials, it is important to assess their dielectric properties, such as dielectric constants, loss tangents, and electrical conductivities. These properties significantly impact the electromagnetic performance, such as impedance matching, radiation efficiency, and resonant frequency of antennas. For instance, studies have demonstrated the effects of bio-based materials' dielectric properties on antenna performance. In [32], researchers explored the impact of materials on impedance matching and resonant frequency. Their investigation focused on the dielectric properties of bio-based materials used as substrates for embedded radio frequency (RF) sensor/antenna modules, revealing potential effects on antenna performance. For practical antenna designs, it is essential to also consider the long-term stability and environmental durability of these materials. Similarly, researchers [89] examined the dielectric properties of agricultural residues, such as rice straw, rice husk, banana leaves, and sugar cane bagasse, for potential applications in microwave communication. The research highlights the suitability of these agricultural waste materials as microwave absorbers and antennas, demonstrating their relevance to advancements in communication technologies. Nevertheless, for antenna applications, it is important to evaluate the consistency of these materials' performance under varying environmental conditions and their scalability for industrial use.

Moisture absorption is another feature that must be considered during material selection. Biodegradable materials may have higher moisture absorption rates compared to their non-biodegradable counterparts. Moisture absorption can alter the dielectric properties of the material, leading to changes in antenna impedance, resonant frequency, and bandwidth, especially in on-body monitoring applications. Additionally, moisture absorption can contribute to material degradation over time, affecting antenna durability and reliability. The presence of humidity in the material can cause air bubbles to form, resulting in a non-homogeneous texture. This can subsequently cause a decrease in antenna efficiency when the material is used as a substrate. As a result, drying is an important preliminary step before the forming process of biodegradable materials [90]. We will discuss more details about the material processing in the next subsection. Reference [91] explores how the performance of antennas changes when liquids are absorbed by the substrate, demonstrating the link between these changes and antenna performance. It introduces a feasibility analysis for a non-wearable, flexible, cost-efficient, and disposable antenna-based sensor implemented on a cellulose filter paper substrate for non-invasive hydration monitoring using sweat.

Biodegradable materials undergo natural degradation over time, primarily through biological mechanisms. The rate of biodegradation varies based on environmental conditions, microbial presence, and material composition. This variability can affect the electrical and mechanical properties of the materials as they decompose, potentially compromising antenna performance and reliability. For example, biodegradable sensors integrated with antennas or RFID tags are widely used in environmental monitoring and precision agriculture for applications such as water quality assessment and real-time monitoring of crop health and soil moisture levels [86], [92]. These sensors are exposed to diverse environmental conditions, including temperature fluctuations and varying moisture levels [71]. Understanding the degradation behavior of biodegradable materials is therefore crucial for ensuring the long-term reliability and accuracy of sensor data.

Additionally, the research in [9] and [93] discuss sensors made from renewable natural materials, emphasizing efficiency, recyclability, and biodegradability. Environmental factors, such as changes in temperature, exposure to ultraviolet (UV) light, and the presence of microorganisms can have a significant impact on biodegradable materials compared to materials that do not biodegrade. This emphasizes the importance of considering environmental sensitivity when selecting material for biodegradable antennas to ensure their long-term stability and performance. In [94], the authors examine recent advancements in biodegradable green electronic materials and their use in sensor technology. These materials are specifically created to meet environmental sustainability goals and offer practical solutions in areas like flexible electronics, temporary electronics, antennas, and various sensing applications. The research highlights the progress made in developing biodegradable electronic materials that can completely break down, thus expanding the possibilities for environmentally friendly electronics and sustainable sensor technologies. Finally, the other feature that must be considered during material selection is compatibility with common manufacturing processes. Biodegradable and renewable materials may exhibit diverse compatibility with common manufacturing processes used for antenna fabrication, such as 3D printing and additive manufacturing, injection molding, and compression molding. Specialized considerations are necessary to effectively process biodegradable materials, thereby influencing antenna design, complexity, and cost.

B. MATERIAL PROCESSING AND CHARACTERIZATION

After selecting the materials, they are put through customized preparation and processing techniques to suit their specific purpose. Methods such as extrusion, injection molding, and 3D printing are used to mold the material into certain shapes, such as sheets or films, which are suited for developing antennas. Surface treatment techniques, such as plasma treatment or chemical etching, can improve attributes such as adhesion and conductivity. Additionally, the inclusion of additives like fillers or reinforcements may further modify the properties of the material to match specific antenna requirements.

The manufacturing process for biodegradable and renewable materials for microwave applications typically has multiple stages, ranging from material preparation to the final assembly of the components. These stages include mixing, molding, curing, and post-processing treatments. Case studies and examples illustrate specific materials used in antenna fabrication, highlighting the challenges faced and the innovative solutions implemented. The authors in [90], describe the fabrication process of a biodegradable antenna substrate using polybutylene succinate (PBS). This material is chosen for its eco-friendly properties, which contribute to the reduction of e-waste and promote environmental sustainability. As shown in Fig. 9, the forming process for the PBS substrate involves a compression process, where the PBS material is compressed to achieve the desired shape and thickness. Initially, the PBS is dried using a LAB-companion oven before the forming process to remove any moisture content, ensuring optimal material properties during fabrication. The dried PBS is then weighed to determine its mass before undergoing the compression process. Subsequently, the dried, weighed PBS is poured into a mold with specific dimensions. The compression machine is used to apply pressure and shape the PBS material into the desired substrate form. Once the forming process is complete, the PBS substrate is allowed to cool and solidify, ready for further antenna fabrication steps. This process highlights the importance of careful material selection and preparation to create biodegradable antenna substrates that meet both functional and sustainability requirements.

Authors in [50], used Tencel fabric to design a monopole antenna for eco-friendly IoT applications. Tencel fabric is derived from a natural cellulosic fiber called Lyocell, which is sourced from the pulp of sustainably farmed trees. The fiber production process of Tencel is eco-friendly due to its closed-loop system, reducing waste disposal by 98%. Tencel fabric is known for its lightness, softness, and suitability for garment production. It is also hygienic, breathable, antistatic, and comfortable against the skin. A close-up view of Tencel fabric (Fig. 10) showcases its texture and appearance, highlight its suitability for wearable devices [50]. The research in [18] investigates the feasibility of using biodegradable PLA as a substrate for a wearable patch antenna. The properties of PLA are enhanced through copolymerization, blending, plasticization, polymer alloy technology, and composite methods.

The process of preparing jute fibers for use in fabric substrate fabrication (see Fig. 11) is studied in [95]. Jute, a natural fiber with a long history of use, is highlighted for its cost-effectiveness, strength, and versatility. Being 100% biodegradable and recyclable, jute offers a sustainable choice for antenna substrates. Its rapid growth cycle makes it particularly suitable for agricultural settings. Jute fibers are obtained from the plant's stem and possess high tensile strength and minimal extensibility, allowing for the production of durable fabrics. Jute's properties, including its ability to breathe, insulate, and resist moisture, make it

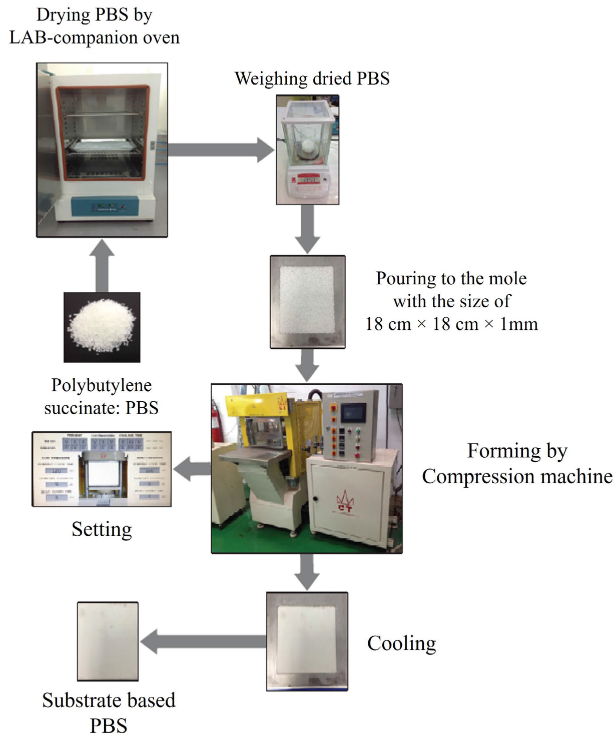


FIGURE 9. Forming process of polybutylene succinate (PBS) substrate [90].

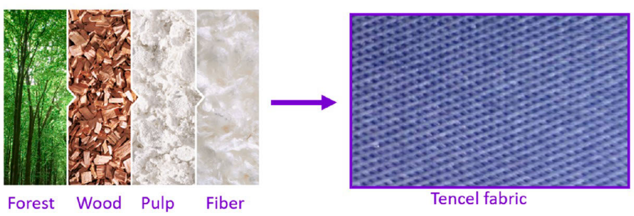


FIGURE 10. Stages in obtaining the Tencel fabric [50].

FIGURE 11. Process of converting jute fibers to jute fabric. (a) Bundle stalk. (b) Retting. (c) Sun-dry. (d) Strapping and washing. (e) Jute yarn. (f) Jute sack [95].

ideal for various applications, including packaging, textiles, and construction [96]. The process of preparing jute fabric (see Fig. 12) involves impregnating the fibers with a thermoset resin, followed by compression molding, cutting, and sanding. Additionally, the pretreatment of jute fabric involves mild scouring with detergent and neutralization with an acetic acid solution, while the synthesis of reinforced jute fabric includes treatment with chemical solutions to impart hydrophobic properties suitable for antenna substrates. The resulting fabric is coated with sodium alginate to enhance its performance in antenna applications.

In addition to biodegradable materials, dielectric materials originated from bio-waste and agricultural waste offer a sustainable and low-cost alternative to conventional materials. In the study [97], the potential use of bio-waste and agricultural waste in the development of dielectric materials has been explored. The possible uses for various materials, including rice straw and husks, coconut shells, oil palm empty fruit bunches, corn husks, and banana leaves, have been discussed in detail. The preparation process typically involves several steps such as collection and sourcing of bio-waste and agricultural waste materials, sorting, and cleaning to remove impurities and contaminants. Processing techniques such as temperature control, chemical treatment, and extraction procedures are then employed to modify the properties of the waste materials and convert them into dielectric materials. These initial steps are crucial in ensuring the purity and quality of the materials before proceeding to the fabrication process, which may vary depending on the desired application of the dielectric materials, such as microwave substrates or antenna components. Materials obtained from agricultural waste can serve as a substitute for traditional printed circuit boards (PCBs) and in antenna applications.

The study in [98] employed palm oil-based polyurethane in conjunction with empty fruit bunch (EFB) as a natural filler for the fabrication of microwave substrates. As demonstrated in Fig. 13, material synthesis and manufacturing process of dried raw EFB powder for microwave substrate involves several steps. Initially, the EFB is dried for a specific duration, typically seven days, to remove moisture and achieve a constant mass. Subsequently, the dried EFB is ground into a fine powder and sieved to separate any impurities or larger particles. Through these steps, the preprocessing for fabrication is completed. The sieved EFB powder is

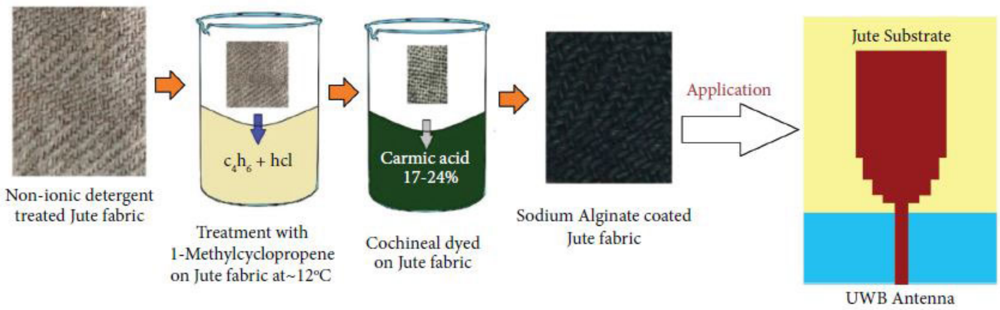


FIGURE 12. Sodium alginte-coated jute synthesis for antenna substrate application [95].

then soaked in water for 24 hours to eliminate the ash content before being dried again until a constant mass is obtained. Following this, the finely ground EFB powder is mixed with a suitable binder, such as polyurethane, to create the polyurethane-empty fruit bunch composite. The resulting powder combination is meticulously blended and then transferred into a mold of rectangular shape, conforming to the desired dimensions. To complete the curing process, the composite is heated with a hot press until it reaches a uniform mass. Finally, the binding process and substrate prototype manufacturing are performed.

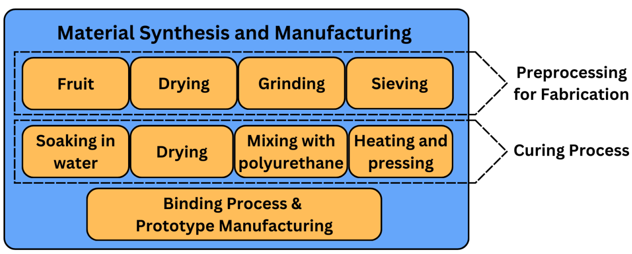


FIGURE 13. Material synthesis and manufacturing process for microwave antenna substrate.

Once the material has been processed, the prototype needs to be characterized to find out its dielectric properties, such as its permittivity and loss tangent, which are crucial for the antenna's performance. Several dielectric measurement techniques are used for the dielectric characterization of different materials, including the transmission line method, coaxial probe (also known as open-ended coaxial probe or OCP), resonant cavity, free space, parallel plate, and inductance measurement method [99]. Every method has its own benefits depending on the equipment available, the forms of material samples, the properties of the materials, and various other aspects [100], [101]. During the computer-aided antenna design process, measured dielectric properties are applied to EM simulation tools. The design will be influenced by material properties.

C. DESIGN REQUIREMENTS FOR ANTENNAS USING BIODEGRADABLE AND RENEWABLE MATERIALS

Achieving optimal antenna performance with biodegradable and renewable materials demands careful design due to their unique properties compared to traditional materials. These properties affect important parameters such as impedance matching, radiation efficiency, and gain. The variability in the electrical properties of biodegradable and renewable materials necessitates meticulous design techniques to ensure the antenna meets the required functionality and efficiency in real-world applications. The dielectric properties of biodegradable materials, such as dielectric constants and loss tangents, significantly impact antenna performance across various parameters, including size, bandwidth, gain, radiation efficiency, and resonant frequency shift. For example, studies on textile patch antennas suggest that fabrics with higher dielectric constants can reduce antenna size [109]. However, it is essential to balance the effect of dielectric constants with other factors, such as the material's loss tangent. While higher dielectric constant materials may offer potential for size reduction and wider bandwidth due to larger variations in resonant frequency, they may also lead to increased dielectric losses, adversely affecting antenna gain and radiation efficiency. Variations in substrate properties can affect the resonant frequency of the antenna, emphasizing the importance of accurately modeling and simulating the effects of biodegradable and renewable materials on antenna resonance to ensure optimal performance across the desired frequency range. Thus, understanding the trade-offs between different antenna characteristics when using biodegradable materials is essential for optimizing antenna design and performance.

The research conducted in [73] proposed a truncated patch antenna design on a jute textile substrate for WPT applications. A comparison of the electromagnetic characteristics of the antenna was made by considering various textiles, including jute, cotton, denim, polyester, and cordura. It was demonstrated that with a jute substrate, the patch size is more compact and the bandwidth is enlarged. However, increased tangent loss reduced both gain and radiation efficiency, posing challenges for long-distance WPT applications. To address this issue and enhance the gain, additional layers of jute were incorporated. For on-body communication antennas, the high dielectric properties of the human body influence the gain by interfering with the induced current in the near-field area [110]. The human body acts as both a dielectric absorber and reflector, impacting system functionality. Researchers have identified

TABLE 3. Biodegradable and renewable antennas with different design techniques and characteristics.

Ref.	Biodegradable Antenna Design Type/Technique	Substrate and Conductive Materials	Operating Frequency Band	Size	Gain/Directivity
[41]	Semicircular patch antenna	Cork substrate, copper-plated Tafetta electroconducting textile	863–873 MHz and 2.4–2.5 GHz	300×300 mm^2 (0.87λ at 868 MHz, 2.45λ at 2.45 GHz)	5.8 dBi at 2.45 GHz and 2 dBi at 868 MHz
[49]	Printed quasi-Yagi–Uda antenna	Kapton substrate, graphene conductor	5–6 GHz	20×30 mm^2 ($0.367\lambda \times 0.550\lambda$)	0.35 dBi
[50]	Coplanar waveguide (CPW)-fed monopole antenna	Tencel substrate, Shieldit Super electrotextile conductor	2.4–2.7 GHz	$28.3 \times 34.5\times 0.26$ mm^3 ($0.241\lambda \times 0.293\lambda \times 0.002\lambda$)	2.17 dBi
[51]	Microstrip patch antenna	Polyolefin substrate, copper foil conductor	902–928 MHz	$100.8 \times 125.8\times 10$ mm^3 ($0.307\lambda \times 0.384\lambda \times 0.03\lambda$)	7 dBi
[61]	Conductive polymer based antenna	Transparent glass substrate, conducting polymer (CPs) PEDOT:PSS	860–960 MHz	55×36 mm^2 ($0.167\lambda \times 0.109\lambda$)	8.6 dBi
[66]	Flexible graphene-based antenna	Different substrates: polyethylene terephthalate (PET), Kapton, polyethylene naphthalate (PEN), polycarbonate (PC), polyvinyl chloride (PVC), paper and silk.	20–100 MHz	45×75 mm^2 ($0.009\lambda \times 0.015\lambda$)	Not given
[81]	3D printed dipole antenna	Wood-based PLA substrate, silver nanoparticle ink conductor	2–3 GHz	Not given	2.1764 dBi
[90]	CPW printed circular monopole	PBS substrate with copper conductor	2400–2500 MHz	50×50 mm^2 ($0.408\lambda \times 0.408\lambda$)	3.12 dBi
[95]	Microstrip patch antenna	Jute substrate with copper conductor	2.2–18.65 GHz	43×40 mm^2 ($1.5\lambda \times 1.4\lambda$)	5.9 dBi
[102]	Printed dipole	BioFila silk and linen filaments as substrate, 3D-printed graphene as conductive part.	2–3 GHz	Not given	-2.29492 dBi for silk-graphene and -2.11608 dBi for linen-graphene
[103]	Bowtie antenna	PLA substrate, copper conductor	2.6 GHz, Sim BW: 0.46 GHz Mea BW: 0.7 GHz	60×30 mm^2 ($0.52\lambda \times 0.26\lambda$)	2.51 dBi
[104]	Rectangular patch	A mixture of PBAT and PHB polymers for substrate, copper conductor	2.4 GHz WLAN, BW: 360 MHz	85×70 mm^2 ($0.68\lambda \times 0.56\lambda$)	3.64 dBi
[105]	Microstrip patch antenna	Cellulose laurate biopolymer substrate with copper conductor	2.45 GHz and 5.8 GHz	$0.4 \times 58\times 54$ mm^3 ($0.003\lambda \times 0.474\lambda \times 0.441\lambda$) ($0.007\lambda \times 1.12\lambda \times 1.044\lambda$) at 2.45 and 5.8 GHz	3 dBi at 2.45 GHz and 5.3 dBi at 5.8 GHz
[106]	4-element patch array	Photo-paper substrate, copper conductor	24 GHz	27×28 mm^2 ($2.16\lambda \times 2.24\lambda$)	7 dBi
[107]	Flexible UWB antenna	Sticky tape substrate, PEDOT:PSS conducting film	3–20 GHz	23×20.25 mm^2 ($0.88\lambda \times 0.78\lambda$)	1.1 to 4.4 dBi
[108]	3D printed dipole antenna	Nylon 680 resin co-polymer filament substrate, (PLA)-based conductive graphene filament	3.2 GHz	$>41.6 \times 17.5$ mm^2 ($0.444\lambda \times 0.187\lambda$)	2.23 dBi

multilayer graphene film, known for its low sheet resistance and excellent electrical conductivity after high-temperature treatment, as a solution. When this graphene film is applied to a paper substrate, it performs comparably to a copper antenna [77]. Furthermore, body tissue and the surrounding environment's high dielectric constant can cause a loading effect that alters the antenna's resonance frequency. In such cases, ultra-wideband (UWB) antennas with biodegradable substrates are preferred [32].

Table 3 provides a list of biodegradable and renewable antennas with various design techniques. The materials used for the antenna substrate and conductive parts are provided, along with the antenna characteristics, such as gain, dimensions, and operating frequency band. Various design techniques, including microstrip patch, bowtie, printed dipole, quasi-Yagi–Uda, coplanar waveguide (CPW)-fed monopole, conductive polymer and graphene-based antennas, and array antennas, have been proposed in the literature. These structures operate across a frequency range from high frequency (HF) to microwave and millimeter-wave frequencies. The approximate sizes of the antennas are presented in terms of wavelength at the center frequency. In the next section, we review manufacturing methods and antenna fabrication techniques.

IV. ANTENNA FABRICATION TECHNIQUES

In order to incorporate biodegradable and renewable materials into the development of microwave components and antennas, researchers have examined a variety of manufacturing techniques, such as 3D printing, inkjet printing, aerosol

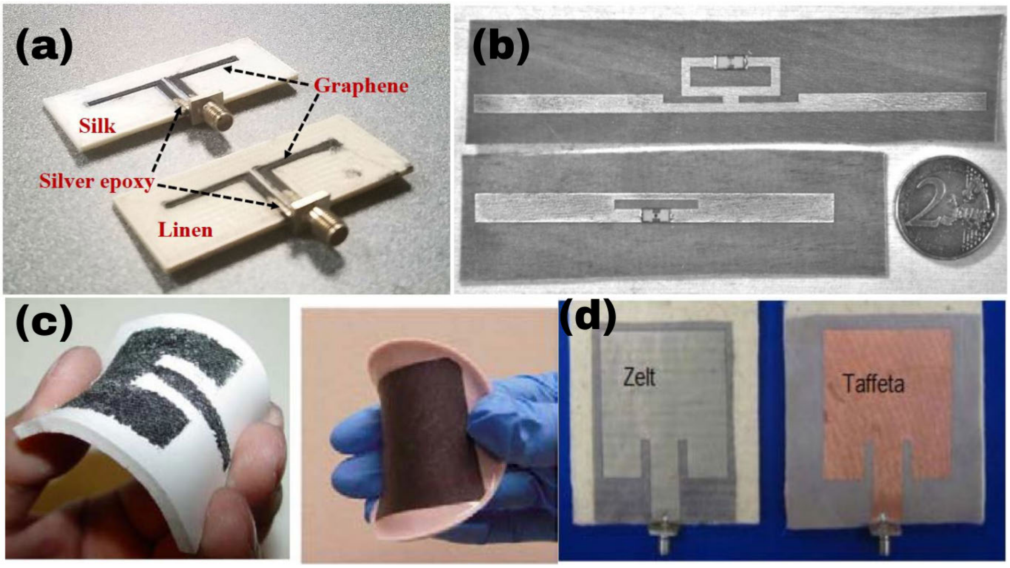


FIGURE 14. Fabrication techniques for biodegradable and renewable antennas. (a) 3D-printed antennas made from 100% biodegradable and renewable substrates [102], (b) Inkjet-printed wide and compact tag antennas with Higgs-3 ICs mounted on plywood samples [111], (c) Highly flexible e-textile antenna printed on a polymer composite [112] (d) Fabricated wearable patch antenna using Zelt and Taffeta electrotextiles for both the patch and ground plane [113].

jet printing, and textile-based methods. Fig. 14 shows some of the fabricated antennas using a variety of manufacturing methods.

A. 3D PRINTED BIODEGRADABLE AND RENEWABLE ANTENNAS

Advancements in additive manufacturing (AM) technology have recently enabled the development of commercial solutions that are rapid, cost-effective, and environmentally benign. These technological developments enable the manufacturing of electronics that exhibit unique features in terms of their dimensions and flexibility. The growing importance of biodegradability in manufacturing processes highlights the need for sustainable practices. By incorporating biodegradable and renewable materials into additive manufacturing techniques such as 3D printing, it becomes possible to create electronic components that fulfill performance criteria while reducing environmental harm during their entire lifespan.

3D printing technology has been employed to fabricate antennas and microwave components using materials such as PLA, acrylonitrile butadiene styrene (ABS), nylon resin co-polymer, and PLA-based conductive graphene. PLA, a biodegradable polymer derived from plants, was used to create a series of 3D-printed bowtie antennas with conductive segments made from ABS [114]. Another study [108] demonstrated the fabrication of a dipole antenna using a blend of nylon resin co-polymer and conductive graphene derived from PLA. Further research [102] explores the potential of manufacturing antennas using biodegradable and sustainable materials, specifically BioFila silk and linen. BioFila, composed of 100% biodegradable material sourced from renewable raw materials, decomposes over time when discarded in landfills or soil. The study presents antennas that claim to be the first manufactured using 100% biodegradable and renewable host substrates, highlighting the innovative integration of sustainable materials in antenna fabrication. Additionally, a bowtie antenna featuring a 3D-printed substrate and annealed copper tape for conductive components was produced in [103].

B. INKJET-PRINTED BIODEGRADABLE AND RENEWABLE ANTENNAS

In recent years, there has been a growing trend towards manufacturing techniques that prioritize environmentally friendly materials, facilitated by additive manufacturing methods such as inkjet printing. Sustainable manufacturing is paramount, driven by the necessity to recycle inkjet-printed antennas and sensors. This highlights the importance of efficiently fabricating components, including substrates and electronic elements, that possess recyclable or biodegradable properties to promote sustainability. Wood and paper-based antennas fabricated using inkjet printing represent a promising sustainable solution for applications such as RFID and WSNs [115], [116], [117], [118]. This precise and flexible printing technique allows researchers to deposit biodegradable and renewable materials onto substrates with high resolution and accuracy, enabling the creation of intricate antenna and sensor designs. By employing eco-friendly conductive inks derived from materials such as graphene, carbon nanotubes, or conductive polymers, researchers have developed antennas that exhibit suitable electrical conductivity while remaining biodegradable [119]. These biodegradable antennas and sensors provide sustainable solutions for environmental sensing, agriculture, and disposable electronics, where sustainability and biocompatibility are crucial [120]. The study in [49] presents a comprehensive methodology for the design, fabrication, and characterization of a flexible antenna printed with graphene ink using inkjet technology, tailored for flexible electronics. The antenna is designed with an optimized quasi-Yagi-Uda pattern that works in the 5–6 GHz frequency range. It has four directors and two reflectors that improve directivity and make the antenna 42% more efficient. Plasma treatment is applied to the flexible Kapton film substrate to enhance ink adhesion and coverage.

In [121], the authors explore the utilization of silver and gold nanoparticle inks printed on eco-friendly substrates like paper and PET using a consumer inkjet printer. The study focuses on designing a dipole antenna with a matching loop for the RFID chip EM4325 at a frequency of 866 MHz, aiming to address the environmental impact associated with traditional production processes and improper disposal of electronic devices. From the literature, it is clear that inkjet printing can be a low-cost technique for large-scale manufacturing of biodegradable and renewable antennas.

C. AEROSOL JET-PRINTED BIODEGRADABLE AND RENEWABLE ANTENNAS

Biodegradable materials are sensitive to factors like humidity, oxygen, and heat, highlighting the need for their fabrication to occur efficiently on a large scale, preferably at low temperatures and in dry environments. A promising avenue for achieving this is through electronic printing technology, which enables rapid prototyping using various functional inks and pastes containing micro and nano materials [122]. Aerosol jet printing, another subset of additive manufacturing technique, has attracted attention for its ability to print material inks on any surface, thereby enabling the design of circuits and devices on unconventional substrates like paper, textiles, and polymers [123].

The previous research emphasizes the potential of aerosol jet printing in fabricating conformal and flexible antenna devices [124]. Polycaprolactone (PCL), chosen for its biodegradability, serves as the polymer of choice. Given that PCL material's dielectric properties were not previously documented due to its predominant use in bioengineering, this study marks the first attempt to measure these properties. The relative permittivity and dielectric loss indicated a low dielectric constant and energy density typical of polymer materials. A bendable structure is created through a process of melting and drawing, and subsequently treated with a hydrogel made from gelatin to reduce any surface imperfections. The ink made of carbon nanotube (CNT) nanomaterial is printed directly onto the prepared PCL. Afterwards, the properties of the antenna are assessed. While the fabricated antenna demonstrates biodegradability, flexibility, and functionality, ensuring adhesion between inks and substrates and generating stable ink aerosols aligned with substrates may pose challenges. Aerosol jet printing has the potential to be another useful antenna fabrication technique.

D. TEXTILE-BASED BIODEGRADABLE AND RENEWABLE ANTENNAS

Textile antennas are defined as ones that use textile materials as both conductive elements and substrates [125]. There is substantial research potential for textile antennas to serve as power receivers for wearable and other portable devices, offering a more comfortable alternative to the cumbersome solutions provided by flexible batteries [126] and rigid traditional batteries [127]. These antennas are made with conductive textiles or fabrics as the radiating element, while other types of fabric are used as the substrate.

The fabrication of textile-based antennas represents a convergence of traditional textile manufacturing techniques with modern electronic component integration, offering a novel approach to wearable technology. Incorporating conductive materials into textiles enables the creation of antennas that seamlessly blend functionality, comfort, and wearability. Various production methods are employed to integrate electronic components, such as conductors, semiconductors, and dielectrics, into textile substrates. These methods range from manual methods like sewing to mechanical processes such as knitting, weaving, embroidery, and braiding. Additionally, non-conductive yarns can be coated with conductive substances, enabling the production of electrically conductive yarns for electronic textile (e-textile) applications [128].

As the field of textile-based antennas continues to advance, there is a growing emphasis on sustainable manufacturing practices. The use of recyclable and/or biodegradable materials in the fabrication of textile-based antennas presents a promising avenue for reducing environmental impact and promoting sustainability throughout the product lifecycle. By incorporating biodegradable substrates, conductors, and other components, manufacturers can create wearable electronics that not only perform effectively but also minimize their ecological footprint. This integration of sustainable practices into textile-based antenna fabrication represents a significant step towards achieving a more environmentally friendly approach to wearable technology development.

The wearable e-textile market is expected to grow significantly in the future, with wearable textiles becoming a part of everyday wear and personalized healthcare applications. Fig. 15 demonstrates the future market demand for wearable e-textiles, showing the percentage of materials used or predicted to be used for e-textiles from 2019 to 2029. It is clear that the global e-textiles and smart clothing market is projected to grow from 2021 to 2028 [129]. Therefore, it is vital that researchers are actively pursuing the development of sustainable electronic fibers and machine fabrication technologies to enable large-scale production of wearable e-textiles, emphasizing the critical role of sustainable product design, including the selection of eco-friendly raw materials and production processes.

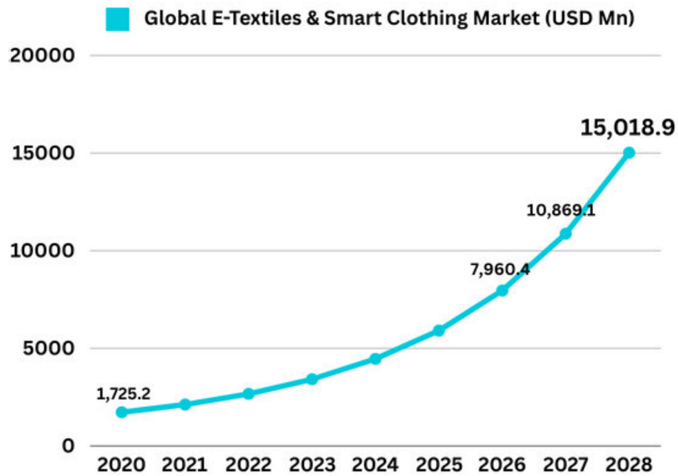


FIGURE 15. Global e-textiles and smart clothing market 2020-2028 [129].

The significance of wearable systems across various fields, as well as the importance of antennas within these systems, are discussed in [18]. The authors highlighted the limitations of traditional antennas fabricated with metals and insulators, emphasizing their rigidity and discomfort when worn. To address these issues, the authors introduced electrotextiles as a novel solution for wearable antennas. These conducting fabrics, such as Zelt and Copper Polyester Taffeta, offer advantages including high conductivity, homogeneity, drapability, and elasticity, as depicted in Fig. 14(d). The study specifically highlighted the use of Taffeta electrotextile in the proposed antenna design, serving as both the radiating patch and ground plane due to its superior conductivity and low surface resistivity. The dielectric substrate for the antenna is a biodegradable, plant-derived polymer PLA, which further enhances its suitability for wearable applications. Moreover, designing a biodegradable antenna for 5G wearable devices, utilizing graphene patterning instead of traditional metallization on a textile substrate, is reported in [130]. This approach promotes environmental sustainability by preventing copper corrosion from repeated garment washing. The antenna patch footprint is minimized through iterative design processes and cut-out insertion, optimizing radiating length within a compact area.

Table 4 lists some potential fabrication techniques for biodegradable and renewable antennas, including the advantages, materials, and implementation challenges for each manufacturing technique.

V. APPLICATIONS OF BIODEGRADABLE AND RENEWABLE ANTENNAS IN GREEN IOT SENSORS

Green manufacturing in IoT devices involves using eco-friendly materials and processes to reduce e-waste and minimize environmental risks. Green materials offer unique electrical and mechanical features for innovative sensing solutions in IoT devices, although they may have limitations in terms of electromagnetic properties and temperature resistance. Fig. 16 illustrates two distinct strategies for producing environmentally friendly devices: (a)–(c) focus on the development of durable, recyclable, and reusable devices; and (d)–(g) center on the utilization of biodegradable electronics [4]. These initiatives hold promise for achieving zero-waste IoT systems, although they may sometimes exhibit reduced performance capabilities.

The deployment of biodegradable and renewable antennas in green IoT sensors opens up a myriad of applications in various sectors such as agriculture [134], [135], healthcare [136], wearable electronics [137], environmental monitoring [138], smart packaging [139], wildlife tracking [140], and smart cities [141]. In the following section, we will review the most popular applications of biodegradable and renewable antennas and sensors, as shown in Fig. 17.

A. AGRICULTURE

Precision Agriculture (PA) plays a vital role in modern farming by boosting food production while minimizing waste. Recent advances, like incorporating IoT sensors, have improved field monitoring for higher yields. However, these sensors often contain non-biodegradable components like batteries and chips, making them costly and environmentally unfriendly. To tackle this, the Degradable Intelligent Radio Transmitting Sensor (DIRTS) was proposed in [92]. It enables remote monitoring of subsoil water levels using drones and wireless technology. DIRTS is made of a simple, miniaturized antenna in a biodegradable polymer, with its frequency adjusting based on soil properties. This simplicity allows for cost-effective, scalable manufacturing, making automated soil distribution feasible. Researchers also have developed plant-wearable sensors for decentralized analysis of pesticides in precision agriculture and food safety [148]. These sensors are made from eco-friendly biopolymeric films and printed devices, specifically using cellulose

TABLE 4. Potential fabrication techniques of biodegradable and renewable antennas.

Ref.	Fabrication Technique	Advantage	Material and Methods	Challenges
[45], [81], [108], [102], [114]	3D Printed	• On-Demand Manufacturing • Rapid Prototyping • Cost Efficiency • Design Flexibility • Complex Assembly Consolidation • Mechanical Reliability	Biodegradable polymers such as PLA, PHA, PCL. Methods include Fused Deposition Modeling (FDM) using biodegradable filaments.	• Limited Material Options: Availability of biodegradable filaments may be limited compared to traditional thermoplastics • Post-Processing Complexity: Some biodegradable materials may require specialized post-processing techniques to achieve desired properties
[111], [115], [116], [120], [121]	Inkjet-printed	• Sustainability • Cost-effectiveness • Precision and Flexibility	Biodegradable inks and substrates such as cellulose-based materials, paper, bio-based polymers.	• Limited Multilayer Printing: Inkjet lacks multilayer capability • Surface Limitation: Inkjet printing requires flat surfaces • Durability: Biodegradable materials may have reduced durability compared to 3D printing
[123], [131], [132]	Aerosol Jet Printing	• Compatibility with Materials • High Precision • Non-Contact Printing	Aerosol deposition of biodegradable inks, nanoparticles, and nanomaterial inks such as Carbon Nanotube (CNT).	• Ensuring adhesion between inks and substrates • Generating stable aerosols of inks aligning with substrates may pose challenges
[112], [128], [130], [133]	Textile-based	• Wearable integration • Relatively low-cost • Lightweight and comfortable • Washable and durable	Biodegradable textile substrates such as organic cotton, bamboo, jute. Methods include weaving and knitting.	• The air gaps deduced by weaving process may cause frequency shift • Reliable performance in different operating circumstances

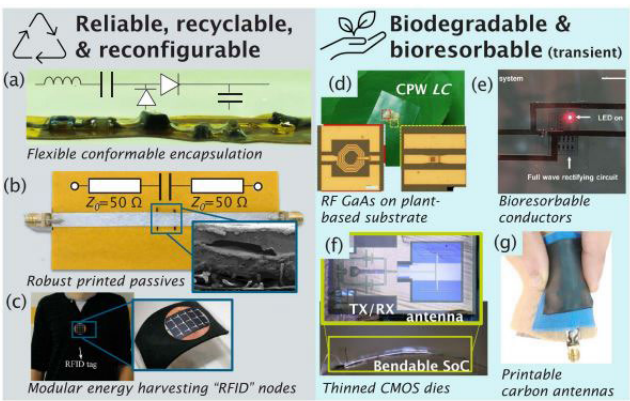


FIGURE 16. **Transitioning from reusable to disposable sustainable devices involves several advancements [4], including: (a) enhancing the durability of flexible RF circuits through robust encapsulation [142]; (b) replacing discrete parts with mechanically and thermally reliable passives [143]; (c) developing programmable and modular flexible sensing platforms [144]; (d) utilizing cellulose nanofibril-based RF passives [70]; (e) implementing bioresorbable Mg antennas and diodes [145]; (f) creating ultra-thin bendable RFICs [146]; and (g) integrating biodegradable carbon antennas [147].**

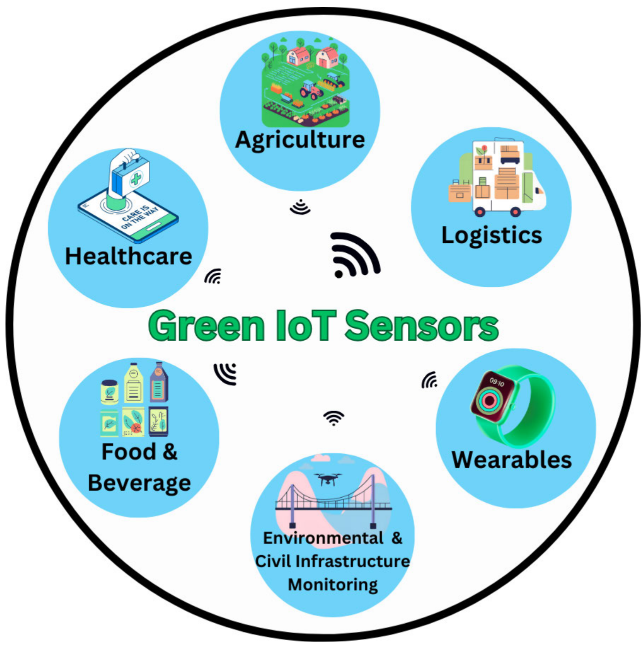


FIGURE 17. **Applications of biodegradable and renewable antennas in green IoT sensors.**

acetate (CA) substrates. The fabrication method involves casting biodegradable CA substrates and depositing a full electrochemical system using the screen printing technique (SPE). The sensors can detect carbendazim and paraquat in agricultural, water, and food samples with high sensitivity and selectivity. Sensors made from biodegradable materials, integrated into precision agriculture IoT systems, offer potential benefits in optimizing water and fertilizer usage. A specific example involves a capacitive moisture sensor, designed to function within a specific frequency range, being

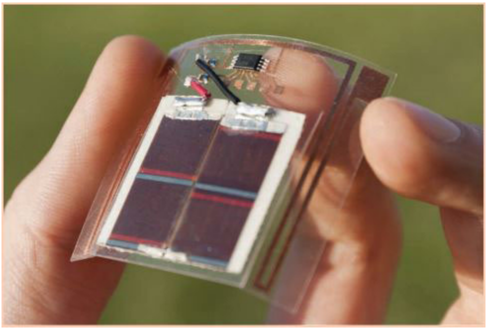


FIGURE 18. RFID-based wireless temperature sensor for precision agriculture [150].

printed onto paper substrate [149]. Enhancements in substrate quality are achieved through the incorporation of cellulose nanofibrils (CNFs). Comparative analysis reveals that sensor performance on the CNF composite matches or exceeds that on conventional materials like polyimide. Furthermore, the infiltration of CNFs enhances the substrate's sensitivity to moisture levels. The fine feature resolution enabled by screen printing on CNF composites makes these sensors suitable for RF passive wireless sensing applications.

Additionally, in efforts to enhance data collection efficiency, scientists have adopted electronic devices such as environmental sensors and camera traps [150], [151]. However, the manual deployment and retrieval of these devices present scalability issues and disrupt ecosystems, contributing to environmental pollution (see Fig. 18). To tackle these challenges, biodegradable sensors have emerged as a promising solution. Utilizing materials like magnesium, iron, zinc, cellulose, silk, and synthetic polymers, these sensors naturally degrade in the environment after use. This not only minimizes ecological disturbance but also reduces the environmental footprint of monitoring activities, offering the potential to gather data on a larger scale and with extended reach.

Additionally, there is significant promise for agricultural applications in the form of biodegradable chipless RFID sensors [152]. This innovative sensor can be deployed in fields to monitor vital conditions such as soil moisture, temperature, and nutrient levels in real time by providing wireless measurements of multiple physical parameters. However, effective resonator encapsulation is crucial to prevent interaction between resonance frequencies [153], which can cause interference, especially when multiple resonators are close together and affected by environmental variations like humidity or temperature.

B. ENVIRONMENTAL AND CIVIL INFRASTRUCTURE MONITORING

Biodegradable sensors present a sustainable approach to advancing ecological research and environmental monitoring efforts. Fig. 19 illustrates the concept of fully biodegradable devices, equipped with sensing elements, power sources, and antennas that autonomously disperse into remote areas in significant quantities [151]. These devices relay real-time data from the field over specific intervals before safely disintegrating in the environment. This approach exemplifies the potential of green IoT sensors to revolutionize data collection while minimizing environmental impact. Moreover, the development of biodegradable RF resonators on paper substrates has emerged as a promising approach to enhance environmental monitoring. Identifying and characterizing biodegradable materials for encapsulation and humidity-sensing layers is crucial for ensuring the functionality of RF resonators [153].

Besides environmental applications, biodegradable sensors can significantly contribute to the monitoring of civil infrastructure. These sensors can be embedded in construction materials, such as concrete, sand, or asphalt, to deliver real-time information on structural integrity, temperature variations, and stress levels [154]. The potential to monitor structural components without the need for disruptive installation methods becomes essential as infrastructure ages. By enabling ongoing monitoring of bridges, roads, and buildings, biodegradable sensors can provide a sustainable solution. These sensors can safely degrade, leaving no harmful leftovers behind once their data-gathering lifecycle is complete. This promotes a more sustainable approach to urban development by improving the longevity and safety of infrastructure and adhering to green building standards.

C. HEALTHCARE

The integration of biodegradable materials in IoT antennas and sensors presents a sustainable approach to advancing healthcare technologies, offering benefits such as environmental sustainability, biocompatibility, flexible design, and cost-effectiveness. By utilizing materials that naturally degrade, the environmental impact is reduced, while the risk of adverse reactions in medical applications is minimized. Moreover, the flexible properties of biodegradable materials enable conformal integration with biological tissues, improving sensor performance. Similar to conventional sensors, biodegradable ones encompass both passive elements, like encapsulation and packaging, and active components, such as sensing mechanisms and circuitry. However, what sets them apart is their composition: rather than relying on traditional metals and plastics, they utilize materials designed to degrade naturally within the body.

Biodegradable sensors can monitor various parameters critical to patient well-being, such as temperature, humidity [155], movement, and sweat [91], [156]. These sensors bring numerous benefits in healthcare, including real-time patient monitoring and personalized medicine by tracking individual patient responses to treatments. Innovative healthcare solutions leveraging biodegradable sensors are emerging, encompassing a variety of applications, from implantable medical devices to wearable health monitoring devices and surgical instruments [157], [158]. The development of

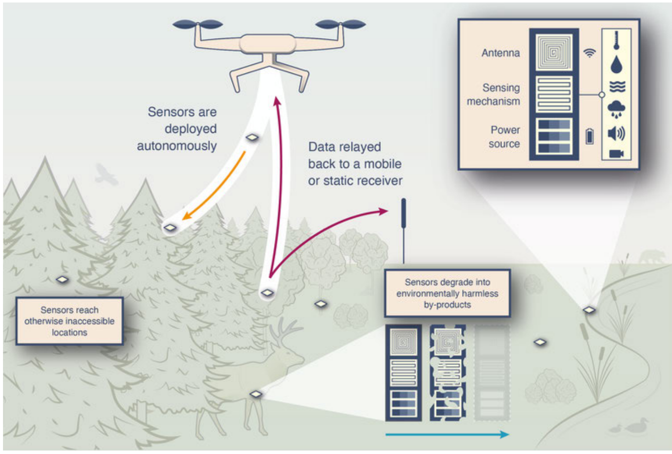


FIGURE 19. Autonomous implementation of biodegradable sensors has the potential to provide ecological data on a larger scale with a reduced environmental impact compared to current methods [151].

biodegradable sensors for disposable diapers represents a significant advancement in self-health monitoring, particularly for vulnerable populations such as infants and the elderly [159]. These sensors have the potential to improve leak management by delivering timely alerts, which could avoid allergic reactions and infections. However, ensuring material durability under varying conditions, integrating these sensors into existing manufacturing processes, and maintaining cost competitiveness while achieving reliable performance are essential for the successful deployment.

Moreover, these sensors can track factors such as air quality and pollution levels, which contribute to overall patient health and well-being. These innovations enable non-invasive monitoring of vital signs, real-time feedback during procedures, and remote communication for drug release control. By eliminating the need for secondary surgeries to remove implanted devices post-investigation [157], biodegradable sensors revolutionize medical procedures and minimize chronic inflammatory responses, offering sustainable healthcare solutions that promote patient comfort while reducing costs and risks.

Biodegradable and biocompatible devices, specifically bioresorbable ones utilizing magnesium (Mg), are applied in wireless biomedical sensing. An example is an all-Mg-based rectenna previously studied for this purpose [145]. In [160], a wireless RF Micro-Electro-Mechanical Systems (MEMS) pressure sensor is proposed. This fully biodegradable sensor holds promise for short-term medical implantation, potentially eliminating the need for extraction post-sensing. Both the inductor and conducting layers utilize a combination of zinc and iron, while biodegradable polymer poly-L-lactide (PLLA) serves as the substrate, with polycaprolactone (PCL) used for bonding and sealing. In [32], the authors proposed the design, fabrication, and measurement of a bio-based RF sensor/antenna element for potential use in healthcare. The module is made from a biocomposite of PLA and sunflower carbon substrate (SCS) with optimized properties. The biocomposite showed comparable dielectric properties to pure SCS, along with increased modulus and hardness. The measurements were performed on various materials and implanted tissue, confirming the effectiveness of the antenna.

D. WEARABLE ELECTRONICS

The rise of wearable technology has ushered in a new era of sensors seamlessly incorporated into clothing, accessories, and even the human body [161], [162]. These sensors, capable of measuring a variety of biomarkers and environmental parameters, have gained popularity due to their affordability, compact size, and ease of data collection via smartphones and wireless connections. They find applications across diverse fields, including clinical diagnostics, environmental monitoring, and forensic chemistry, offering substantial value for both research and commercial purposes [163]. Market analysis predicts a significant increase in wearable device sales, with millions of units expected to be sold globally. With the increasing integration of wearable devices into the IoT, the wearable market is projected to expand into a multibillion-dollar industry by 2027 [164]. In this context, biodegradable sensors have emerged as a promising solution, offering controlled degradation and compatibility with the environment. Crafted from materials such as biodegradable metals, paper substrates, and conductive polymer composites, these sensors serve various purposes, from temporary body implants to environmental monitoring. Their biodegradability is particularly advantageous for medical applications, mitigating the risks of rejection and inflammation.

Researchers have achieved biodegradable antennas using polystyrene sulfonate (PEDOT:PSS) screen-printed fabric [165] and carbon black [147] for integrated green wearable electronic networks. Printing biodegradable conductive tracks on degradable substrates is a key approach for reducing the disposal waste associated with traditional substrates like FR4, adhesives, and the waste produced during the photochemical etching process.

The authors in [166] discuss the challenges and solutions related to selecting polymers as antenna substrates for emerging 5G applications, with a focus on IoT devices and smart wearables. Two polymers, polymethyl methacrylate (PMMA) and polydimethylsiloxane (PDMS), are explored as potential substrates for flexible microstrip antennas operating at 5.8 GHz. The study highlights the compact design of the proposed antennas and evaluates their performance, demonstrating that PMMA outperforms PDMS in terms of gain. Both substrates demonstrate improved performance when subjected to bending circumstances and possess exceptional impedance matching. The study affirms that PMMA and PDMS are suitable for achieving effective performance of flexible microstrip antennas for IoT device technologies in the Sub-6 GHz frequency range.

The researchers in [167] propose a solution for fabricating a liquid metal circuit on textile substrates using the screen printing method. They demonstrate that breakages in the liquid metal circuit on cotton or Lycra elastic fabrics can be repaired by pressing or heating, and the circuits can be removed using a sodium hydroxide solution. Additionally, the liquid metal circuit functions as a pressure switch for thermal management systems, allowing precise temperature control by adjusting the applied pressure. It also functions as a flexible near-field communication (NFC) antenna, providing identification capabilities such as replacing campus cards and improving child safety. Furthermore, the liquid metal-based fabric sensors can accurately detect human motion in real time, highlighting their significant potential for flexible wearable electronics.

The authors in [168] discuss the development of a plastic-free RF device in response to environmental concerns surrounding wearable and flexible devices for 5G and 6G networks. The study introduces a biocompatible Planar Inverted-F Antenna (PIFA) fabricated on a chitosan substrate, offering a compact footprint and operating within the sub-6 GHz band of the 5G spectrum. The prototype demonstrates promising performance with a realized gain of 1 dBi. These findings highlight the potential of chitosan as a dielectric substrate for plastic-free antennas, particularly in the development of sustainable healthcare IoT devices. Additionally, the study in [169] focuses on designing eco-friendly antennas using PLA substrate and carbon nanotubes (CNTs) as the conductive material. The antennas exhibit impressive performance metrics, making them suitable for a broad spectrum of emerging applications within the sub-6 GHz band.

Moreover, the development of bio-compatible, flexible temperature sensors for wearable health monitoring and thermal perception has been proposed, particularly for continuous monitoring of body temperature and other vital signs in personal health devices [170]. In another study, an evaluation was conducted of a flexible, polymer-based temperature sensor designed for continuous body temperature monitoring. The sensor, developed using a PEDOT:PSS + GO composition on a flexible PET substrate, highlights significant sensitivity of 1.205%/°C, achieved through careful miniaturization and optimization of the active layer stacking [171].

E. FOOD AND BEVERAGE

The emergence of the Internet of Disposable Things (IoDT) represents a significant advancement in wireless sensor networks due to its compact, disposable design, and affordability. This pioneering concept facilitates the integration of diverse devices at a reasonable cost, functioning for a specified duration before disposal. By utilizing environmentally friendly materials such as paper, IoDT devices exemplify the convergence of IoT and sustainability, signaling a future that is advanced in technology and cares about the environment. Researchers are currently exploring the use of such materials to mitigate the ecological footprint of conventional IoT devices. These wireless IoDT sensors have versatile applications, enabling the real-time collection of data in diverse scenarios. For instance, a paper-based sensor affixed to food packaging can accurately monitor food freshness, facilitating the disposal of both the packaging and sensor together after usage [172]. Fabricated using laser-induced graphene (LIG) on commercially available paper packaging, the sensor can simultaneously monitor food temperature and trimethylamine (TMA) gas concentration. Known as laser-induced paper sensors (LIPS), it integrates seamlessly into various shapes of paper packaging without requiring additional processing or electronics. For example, it can be embedded inside a milk carton to detect the presence of TMA or placed on the exterior of a paper cup to monitor temperature [173]. The sensor communicates wirelessly via Bluetooth to a mobile device for convenient monitoring.

Nonetheless, a significant hurdle for IoDT devices lies in securing a sustainable power source. Addressing this challenge, researchers have engineered a micro biobattery capable of powering IoDT sensors [174]. This breakthrough enables the creation of disposable sensors and batteries for IoDT applications, thus advancing sustainability within IoT technology.

The research in [175] introduces a flexible antenna sensor embedded in denim jeans fabric for sensing H_2O levels. Graphene oxide (GO) is applied to the defected ground plane for sensor functionality. The resonance frequency of the antenna, at 5.52 GHz, changes linearly with the H_2O content, with a frequency sensitivity of approximately 203 MHz per 10% relative humidity (RH). Notably, the designed antenna sensor can differentiate between fresh and dried grapes based on H_2O detection. The wireless passive antennas introduced in [176] involve the development of antennas on silk substrates, operating across diverse frequency ranges. These antennas are engineered to conformally adhere to curved surfaces, including food items, enabling non-invasive monitoring of food quality. Moreover, the study in [177] aimed to investigate the technical feasibility of manufacturing

UHF RFID tags utilizing biodegradable PLA for the purpose of food traceability. The research investigated the dielectric properties of PLA and how they change when exposed to environmental conditions. With the increasing importance of food security in the world, biodegradable and renewable antennas will serve well to reduce e-waste in the sector.

F. LOGISTICS

In the modern age of technological advancement, known as the Fourth Industrial Revolution (Industry 4.0), green logistics has emerged as an imperative strategy to reduce environmental impact while enhancing operational efficiency. Through the adoption of multi-sensor tracking devices and IoT technology, companies aim to minimize pollution, decrease transportation costs, and optimize packaging methods. These IoT-enabled devices, including RFID technology, monitor essential parameters such as temperature, pressure, humidity, and light, ensuring the safe transportation of goods with minimal environmental harm. Real-time data monitoring and automation, facilitated by green IoT sensors, make logistics operations more sustainable and resilient.

The potential of PEDOT:PSS as a cost-effective conducting polymer film has been explored in [61], [178], and [179]. Typically used in electronic devices, this material shows promise in creating compact broadband antennas for RFID UHF applications. These antennas are crucial for green electronics and biosensor uses. By applying transparent conductive film on recyclable glass substrates, visually appealing antennas can be crafted for applications like optical displays and sensors. Despite PEDOT:PSS's lower conductivity compared to copper, initial findings suggest reasonable performance levels, indicating the potential of such materials in eco-friendly technology applications such as traceability and authentication for tracking chains.

In [178], the authors examined how conformable packaging designs impact the performance of soft polydimethylsiloxane (PDMS)-based flexible pressure sensors across diverse surface conditions and load levels. Under various testing scenarios, these flexible and reusable sensors showed a reduced limit of detection by up to 30%.

The integration of wireless sensors based on paper substrates with RFID tags using printed electronics, enabling applications such as object identification, localization, position tracking, and environmental sensing [65]. Additionally, research has been made for graphene RFID tags that are very adaptable and may be readily discarded. These tags are intended for near-field communication in consumer electrical products [66]. These tags are designed for compatibility with high industrial standards and can be integrated into sensor modules on paper substrates with ease of fabrication using printed technologies.

VI. RESEARCH CHALLENGES, PROSPECTS AND FUTURE POTENTIAL

This section focuses on the current areas of study and the challenges that need to be addressed in relation to biodegradable and renewable antenna technology for green IoT sensors. With the increasing use of IoT sensors in numerous industries, it is becoming more important to address the sustainability challenges related to e-waste. The future of biodegradable and renewable antennas presents a promising environment abundant in innovation, sustainability, and breakthrough potential. However, as this field progresses, there are several areas of research challenges that need to be addressed.

A. RESEARCH CHALLENGES

1) RECYCLABILITY AND LIFETIME

Recyclability and lifetime are important factors in the development of biodegradable and renewable antennas and sensors. It is imperative that these components maintain their performance over an appropriate lifespan, even under diverse environmental conditions, to ensure their practical application. Meanwhile, biodegradable antennas and sensors should be developed with recyclability in mind, enabling their recycling or safe decomposition at the end of their lifecycle. Research into the optimal balance between durability and biodegradability is essential, as the materials must retain functionality for the necessary duration while also being capable of efficient breakdown or recycling once they are no longer needed.

2) DURABILITY AND ENVIRONMENTAL IMPACT

The development of biodegradable and renewable antenna technology involves additional research aspects, such as durability and environmental impact. A key challenge is ensuring that these antennas maintain their performance under adverse environmental conditions, such as exposure to humidity, temperature fluctuations, and mechanical stress. Encapsulation is critical as it allows sensors to withstand various environmental conditions while maintaining optimal performance. The use of PDMS and textile-based materials in the form of coating and encapsulation can significantly enhance the durability of biodegradable and renewable antennas in more harsh environments. Notably, beeswax-coated resonators exhibited exceptional encapsulation characteristics by maintaining the stability of the resonance frequency at varying humidity levels [153]. In addition, the study in [170] examined the performance deviation of the sensor compared to its original performance before and after encapsulation, which is essential to protect sensors in green IoT applications.

3) INTEGRATION WITH IOT DEVICES

Integration of biodegradable and renewable antennas with IoT devices is another key area of focus for sustainable technology advancement. These antennas must seamlessly work alongside other components, such as sensors, processors, and power sources, without sacrificing performance. The challenge lies in ensuring that the materials used in the antennas are compatible with existing IoT architectures while maintaining eco-friendly properties. Furthermore, research into optimal antenna designs that can adapt to the compact and diverse requirements of IoT devices will be essential for effective integration.

Notable trade-offs between sustainability and technical performance also require consideration. For example, while biodegradable and renewable antennas can contribute to environmental benefits, their radiation performance needs to be examined to compete with that of traditional materials, potentially impacting signal strength and range. Additionally, the complexity of integrating these materials into existing systems may require more robust designs, which could counteract some of the sustainability goals by increasing resource consumption during manufacturing. Balancing these factors will be crucial in advancing the field.

Future studies could explore innovative solutions that enhance radiation efficiency while minimizing the ecological footprint, ensuring that the transition to biodegradable technologies does not compromise the effectiveness of IoT infrastructures. In the following subsections, we will review several prospects and future potential works that highlight emerging trends in the field.

B. DESIGN PERSPECTIVE

The increase in the deployment of IoT sensors has highlighted the urgent requirement for sustainable design techniques. It is essential to design antennas that are both biodegradable and renewable in order to enable the future generation of environmentally friendly IoT sensors. Future developments should prioritize on the efficiency, compactness, cost-effectiveness, and practical feasibility of antennas for a wide range of IoT applications. To meet the requirements of biodegradable and renewable materials, improving antenna designs will require addressing unique limitations, such as achieving optimal performance while preserving environmental sustainability. The incorporation of biodegradable and renewable materials presents distinct challenges and opportunities. It is essential to develop miniature antennas that maintain high performance in terms of gain, radiation efficiency, and desirable radiation patterns. For instance, in wearable applications, antennas must be miniaturized while maintaining satisfactory performance near human tissue, such as being impervious to power reception degradation due to coupling effects. Additionally, antennas should be designed to withstand environmental factors, particularly in applications like agricultural monitoring, where durability and resistance to weather conditions are paramount.

C. ANTENNA DESIGN USING META-HEURISTICS AND ARTIFICIAL INTELLIGENCE (AI)

The application of meta-heuristic algorithms in antenna design for biodegradable and renewable sensors has promising potential. Meta-heuristic algorithms such as evolution cycle-based optimization [180], [181], [182], [183], intelligence behaviors-based optimization [184], [185], [186], [187], mathematics and physics-based algorithms [188], [189] can all contribute to the optimization of antenna designs. These methods can help achieve innovative structures that balance performance with environmental sustainability, which is not feasible with conventional electromagnetic simulation tools. Moreover, machine learning (ML) techniques can further enhance the design process, allowing for the creation of antennas that are both efficient and environmentally friendly. New innovations in biodegradable and renewable antennas are certain to be cost-effective and energy efficient when the power of ML is applied to the problem. We also need computational tools to explore the vast number of possible antenna structures, designs, and substrate materials and apply their inferences to evaluate novel integrated antennas and IoT sensors.

D. FABRICATION TECHNIQUES

The advancement of biodegradable and renewable antennas heavily relies on the emergence of fabrication methods. Technologies like 3D printing, inkjet printing, and flexible conductive textiles offer expanded possibilities for applications. These techniques enable the development of antennas that can be seamlessly incorporated into sensor modules, maximizing space utilization and promoting environmental sustainability.

3D printing has the potential to transform the development of biodegradable antennas by enabling the creation of complex, custom designs using renewable materials such as PLA or wood-fill composites. This technology facilitates efficient material utilization, minimizes waste, and allows for low-cost on-demand production, making it ideal for developing specific antenna and sensor structures. However, for complicated sensors, robustness is essential, and this factor must be carefully considered when using 3D printing technology. Additionally, addressing challenges related to material selection and properties is essential to ensuring the feasibility of large-scale manufacturing.

Furthermore, inkjet printing provides an economical and scalable method for producing flexible, biodegradable antennas. Depositing conductive inks onto renewable substrates such as paper or biopolymers facilitates the production of miniaturized, lightweight antennas appropriate for disposable or wearable IoT devices. The procedure is energy-efficient and facilitates mass production via roll-to-roll techniques. The main obstacle in revolutionizing antenna development is enhancing the conductivity and durability of biodegradable inks to match the performance of conventional materials.

Additionally, flexible conductive textile technologies can revolutionize antenna designs by integrating conductive fibers into biodegradable fabrics, resulting in antennas that are flexible, lightweight, and wearable. Textile-based antennas can be mass-produced by automated methods; however, additional innovation is required to create biodegradable conductive fibers that maintain performance under mechanical stress, thereby ensuring reliable performance in dynamic circumstances.

Ultimately, researching composite materials including nanomaterials for antenna substrates and conductors is essential not only for enhancing performance but also for enabling efficient manufacturing processes while maintaining biodegradability. It is crucial to conduct a cost-effective investigation into these new fabrication methods and manufacturing techniques to promote the wider use of sustainable antenna designs by minimizing costs.

E. INTEGRATION WITH EXTERNAL RF CIRCUITS AND IOT SENSORS

Practical applications require the efficient integration of biodegradable and renewable antennas with matching circuits, rectifiers, storage devices, IoT sensors, and other subsystems. The antenna design must consider factors such as easy mounting and compatibility with planar circuits. It is necessary to address the issues that arise from the close proximity to other electronic components and potential interactions that can negatively affect the antenna's functionality. By incorporating simulation and optimization techniques throughout the design phase, it is possible to minimize these problems and guarantee reliable performance over the desired band of frequencies in practical scenarios.

F. ANTENNA PERFORMANCE ASSESSMENT

Conducting a comprehensive assessment of biodegradable and renewable antennas is required to verify their effectiveness in practical applications. While most studies focus on antenna gain, radiation efficiency and radiation patterns, it is critical to highlight the antennas' overall performance in practical uses, particularly IoT sensing applications. Conducting performance evaluations in real-life scenarios, taking into account factors like path loss, noise-prone channels and environmental factors, will be essential for validating the practical effectiveness of these antennas.

VII. CONCLUSION

In summary, the outlook for biodegradable and renewable antennas in IoT sensors appears highly promising. With increasing emphasis on sustainability, these technologies offer a pathway towards a more environmentally friendly world. By leveraging technological advancements, addressing current challenges, and seizing market opportunities, biodegradable sensors stand poised to reduce e-waste, revolutionize industries, mitigate environmental impact, and foster sustainability.

This review underscores the crucial roles of eco-friendly materials like biopolymers, bio-based composites, and natural fibers in advancing sustainable communication technologies. Their sustainability, biodegradability, and recyclability make them ideal for developing antennas used in green IoT systems. Various antenna designs have been explored, focusing on performance and practical applications that promote environmental responsibility.

Ongoing research into biodegradable and renewable materials for microwave technology and their integration into IoT systems reflects growing interest and potential in these areas. To meet industry standards and facilitate widespread adoption, future research should prioritize enhancing the performance, scalability, and applicability of biodegradable and renewable antennas and sensors. Key performance metrics that require enhancement include manufacturing cost, efficiency, reliability, and usability. Low-cost manufacturing is crucial for ensuring that biodegradable and renewable antennas are economically viable for mass production.

Future research can focus on advanced fabrication techniques such as 3D printing, inkjet printing, aerosol jet printing, and textile-based antennas. These methods are expected to minimize material waste while facilitating rapid prototyping and design customization. Usability challenges related to antenna arrays will also be addressed. As these technologies are integrated into various applications, it is essential to ensure their adaptability to different environments and user needs. Additionally, developing modular designs for easy assembly and reconfiguration will enhance the deployment of biodegradable antennas in diverse settings. Efforts will also target improving the mechanical properties of biodegradable materials to ensure that these antennas withstand the rigors of real-world applications, further driving their adoption.

By fostering innovative solutions and promoting collaboration among researchers, practitioners, and industry stakeholders, we can establish a future where sustainable IoT sensor technologies become commonplace. Addressing design challenges and pursuing the identified research directions will be crucial in establishing biodegradable antennas and sensors as impactful technologies across diverse fields like healthcare, agriculture, environmental monitoring, wearable electronics, logistics, and the food and beverage industry. The journey towards a more sustainable world continues, with biodegradable and renewable sensors marking a significant stride towards widespread adoption of eco-friendly and efficient communication technologies.

REFERENCES

[1] B. Muneer, F. K. Shaikh, and Q. Zhu, *Antennas for IoT Application: An RF and Microwave Aspect of IoT*. Hershey, PA, USA: IGI Global, 2020, pp. 180–192.

[2] R. Roges and P. K. Malik, "Planar and printed antennas for Internet of Things-enabled environment: Opportunities and challenges," *Int. J. Commun. Syst.*, vol. 34, no. 15, p. e4940, Aug. 2021.

[3] A. Costanzo, E. Augello, G. Battistini, F. Benassi, D. Masotti, and G. Paolini, "Microwave devices for wearable sensors and IoT," *Sensors*, vol. 23, no. 9, p. 4356, Apr. 2023.

[4] H. Rahmani, D. Shetty, M. Wagih, Y. Ghasempour, V. Palazzi, N. B. Carvalho, R. Correia, A. Costanzo, D. Vital, F. Alimenti, J. Kettle, D. Masotti, P. Mezzanotte, L. Roselli, and J. Grosinger, "Next-generation IoT devices: Sustainable eco-friendly manufacturing, energy harvesting, and wireless connectivity," *IEEE J. Microw.*, vol. 3, no. 1, pp. 237–255, Jan. 2023.

[5] Z. Sheng, C. Mahapatra, C. Zhu, and V. C. M. Leung, "Recent advances in industrial wireless sensor networks toward efficient management in IoT," *IEEE Access*, vol. 3, pp. 622–637, 2015.

[6] K. Singh, M. Saikia, K. Thiyagarajan, D. Thalakotuna, K. Esselle, and S. Kodagoda, "Multi-functional reconfigurable intelligent surfaces for enhanced sensing and communication," *Sensors*, vol. 23, no. 20, p. 8561, Oct. 2023.

[7] P. Bontinck, J. Bricout, T. Grant, and G. Legoe, "E-product stewardship in Australia: Evidence report," in *A Report Prepared for the Commonwealth Department of Agriculture, Water and the Environment By Iceni Group and Lifecycles*. Canberra, ACT, Australia: Australian Government, 2021.

[8] Y. Sui, M. Atreya, S. Dahal, A. Gopalakrishnan, R. Khosla, and G. L. Whiting, "Controlled biodegradation of an additively fabricated capacitive soil moisture sensor," *ACS Sustain. Chem. Eng.*, vol. 9, no. 6, pp. 2486–2495, Feb. 2021.

[9] B. Piro, H. V. Tran, and V. T. Thu, "Sensors made of natural renewable materials: Efficiency, recyclability or biodegradability—The green electronics," *Sensors*, vol. 20, no. 20, p. 5898, Oct. 2020.

[10] F. Alimenti, V. Palazzi, C. Mariotti, P. Mezzanotte, R. Correia, N. B. Carvalho, and L. Roselli, "Smart hardware for smart objects: Microwave electronic circuits to make objects smart," *IEEE Microw. Mag.*, vol. 19, no. 6, pp. 48–68, Sep. 2018.

[11] G. Azzellino, A. Grimoldi, M. Binda, M. Caironi, D. Natali, and M. Sampietro, "Fully inkjet printed organic photodetectors with high quantum yield," *Adv. Mater.*, vol. 25, pp. 6829–6833, Sep. 2013.

[12] M. H. Overgaard, M. Kühnel, R. Hvidsten, S. V. Petersen, T. Vosch, K. Nørgaard, and B. W. Laursen, "Highly conductive semitransparent graphene circuits screen-printed from water-based graphene oxide ink," *Adv. Mater. Technol.*, vol. 2, no. 7, May 2017, Art. no. 1700011.

[13] NMSC (NMSC). (2023). *Biodegradable Sensors Market By 2030*. Accessed: Sep. 2023. [Online]. Available: https://www.nextmsc.com/report/biodegradable-sensors-market

[14] M. A. Albreem, A. M. Sheikh, M. H. Alsharif, M. Jusoh, and M. N. M. Yasin, "Green Internet of Things (GIoT): Applications, practices, awareness, and challenges," *IEEE Access*, vol. 9, pp. 38833–38858, 2021.

[15] N. G. Shimpi, *Biodegradable and Biocompatible Polymer Composites: Processing, Properties and Applications*. Cambridge, U.K.: Woodhead, ch. 1, 2018.

[16] S. S. Ray and M. Okamoto, "Biodegradable polylactide and its nanocomposites: Opening a new dimension for plastics and composites," *Macromolecular Rapid Commun.*, vol. 24, no. 14, pp. 815–840, Sep. 2003.

[17] Z. Zhang and S.-S. Feng, "The drug encapsulation efficiency, in vitro drug release, cellular uptake and cytotoxicity of paclitaxel-loaded poly(lactide)–tocopheryl polyethylene glycol succinate nanoparticles," *Biomaterials*, vol. 27, no. 21, pp. 4025–4033, Jul. 2006.

[18] S. Ullah and J. A. Flint, "Electro-textile based wearable patch antenna on biodegradable poly lactic acid (PLA) plastic substrate for 2.45 GHz, ISM band applications," in *Proc. Int. Conf. Emerg. Technol. (ICET)*, Dec. 2014, pp. 158–163.

[19] M. S. Kim, H. Chang, L. Zheng, Q. Yan, B. F. Pfleger, J. Klier, K. Nelson, E. L.-W. Majumder, and G. W. Huber, "A review of biodegradable plastics: Chemistry, applications, properties, and future research needs," *Chem. Rev.*, vol. 123, no. 16, pp. 9915–9939, Jul. 2023.

[20] A. A. Kumar, K. Karthick, and K. Arumugam, "Biodegradable polymers and its applications," *Int. J. Bioscience, Biochemistry Bioinf.*, vol. 1, pp. 173–176, Jan. 2011.

[21] C. Bastioli, *Handbook of Biodegradable Polymers*. Berlin, Germany: Walter de Gruyter GmbH & Co KG, 2020.

[22] A. K. Mohanty, M. Misra, and G. Hinrichsen, "Biofibres, biodegradable polymers and biocomposites: An overview," *Macromolecular Mater. Eng.*, vols. 276–277, no. 1, pp. 1–24, Mar. 2000.

[23] M. Saini, "Implant biomaterials: A comprehensive review," *World J. Clin. Cases*, vol. 3, no. 1, p. 52, 2015.

[24] M. Koller and A. Mukherjee, "Polyhydroxyalkanoates (PHAs)—Production, properties, and biodegradation," in *Biodegradable Polymers in the Circular Plastics Economy*. Hoboken, NJ, USA: Wiley, May 2022, pp. 145–204.

[25] Z. Li, J. Yang, and X. J. Loh, "Polyhydroxyalkanoates: Opening doors for a sustainable future," *NPG Asia Mater.*, vol. 8, no. 4, p. e265, Apr. 2016.

[26] A. Surendren, A. K. Mohanty, Q. Liu, and M. Misra, "A review of biodegradable thermoplastic starches, their blends and composites: Recent developments and opportunities for single-use plastic packaging alternatives," *Green Chem.*, vol. 24, no. 22, pp. 8606–8636, 2022.

[27] T. Jiang, Q. Duan, J. Zhu, H. Liu, and L. Yu, "Starch-based biodegradable materials: Challenges and opportunities," *Adv. Ind. Eng. Polym. Res.*, vol. 3, no. 1, pp. 8–18, Jan. 2020.

[28] A. Samir, F. H. Ashour, A. A. A. Hakim, and M. Bassyouni, "Recent advances in biodegradable polymers for sustainable applications," *Npj Mater. Degradation*, vol. 6, no. 1, p. 68, Aug. 2022.

[29] M. J. Tan, C. Owh, P. L. Chee, A. K. K. Kyaw, D. Kai, and X. J. Loh, "Biodegradable electronics: Cornerstone for sustainable electronics and transient applications," *J. Mater. Chem. C*, vol. 4, no. 24, pp. 5531–5558, 2016.

[30] F. Kazemi, F. Mohanna, and J. Ahmadi-Shokouh, "Nondestructive high-resolution microwave imaging of biomaterials and biological tissues," *AEU-Int. J. Electron. Commun.*, vol. 84, pp. 177–185, Feb. 2018.

[31] P. Tseng, B. Napier, L. Garbarini, D. L. Kaplan, and F. G. Omenetto, "Functional, RF-trilayer sensors for tooth-mounted, wireless monitoring of the oral cavity and food consumption," *Adv. Mater.*, vol. 30, no. 18, Mar. 2018, Art. no. 1703257.

[32] A. Tesser, A. Alemaryeen, J. Lewis, A. Alshami, M. Haghshenas, and S. Noghanian, "Synthesis and use of bio-based dielectric substrate for implanted radio frequency antennas," *IEEE Access*, vol. 7, pp. 123268–123279, 2019.

[33] G. Chandra and A. Pandey, "Biodegradable bone implants in orthopedic applications: A review," *Biocybernetics Biomed. Eng.*, vol. 40, no. 2, pp. 596–610, Apr. 2020.

[34] F. D. Al-Shalawi, A. H. M. Ariff, D.-W. Jung, M. K. A. M. Ariffin, C. L. S. Kim, D. Brabazon, and M. O. Al-Osaimi, "Biomaterials as implants in the orthopedic field for regenerative medicine: Metal versus synthetic polymers," *Polymers*, vol. 15, no. 12, p. 2601, Jun. 2023.

[35] W. Khan, V. G. S. Challa, R. Langer, and A. J. Domb, *Biodegradable Polymers for Focal Delivery Systems*. Berlin, Germany: Springer, Dec. 2013, pp. 3–32.

[36] M. Prakasam, J. Locs, K. Salma-Ancane, D. Loca, A. Largeteau, and L. Berzina-Cimdina, "Biodegradable materials and metallic implants—A review," *J. Funct. Biomaterials*, vol. 8, p. 44, Sep. 2017.

[37] Y. Li, Y.-X. Guo, and S. Xiao, "Orientation insensitive antenna with polarization diversity for wireless capsule endoscope system," *IEEE Trans. Antennas Propag.*, vol. 65, no. 7, pp. 3738–3743, Jul. 2017.

[38] H. Shi, T. Liu, C. Fu, L. Li, L. Tan, J. Wang, X. Ren, J. Ren, J. Wang, and X. Meng, "Insights into a microwave susceptible agent for minimally invasive microwave tumor thermal therapy," *Biomaterials*, vol. 44, pp. 91–102, Mar. 2015.

[39] R. Narang, S. Mohammadi, M. M. Ashani, H. Sadabadi, H. Hejazi, M. H. Zarifi, and A. Sanati-Nezhad, "Sensitive, real-time and non-intrusive detection of concentration and growth of pathogenic bacteria using microfluidic-microwave ring resonator biosensor," *Sci. Rep.*, vol. 8, no. 1, p. 15807, Oct. 2018.

[40] S. M. de Holanda, J. P. da Silva, I. de S. Queiroz, H. D. de Andrade, J. R. F. Guerra, J. de A. P. Magno, M. S. de Aquino, M. V. de Melo, and N. O. L. Filho, "Microstrip antenna based on knitted fabrics with biodegradable synthetic fibers," *J. Mater. Sci., Mater. Electron.*, vol. 28, no. 20, pp. 15118–15126, Jul. 2017.

[41] H. F. Khalili, S. Lemey, O. Caytan, T. Deckmyn, S. Agneessens, D. V. Ginste, and H. Rogier, "Biodegradable dual semicircular patch antenna tile for smart floors," *IEEE Antennas Wireless Propag. Lett.*, vol. 18, pp. 368–372, 2019.

[42] K. Zeouga, L. Osman, A. Gharsallah, S. Sankaralingam, and B. Gupta, "Efficient rectifier design on jute material for wireless power transmission," in *Proc. IEEE 15th Medit. Microw. Symp. (MMS)*, Nov. 2015, pp. 1–3.

[43] S. Roy, S. Ghosh, P. B. Saha, M. S. Singh, A. Sarkhel, and S. Pattanayak, "Design and analysis of low cost biodegradable substrate material for microwave device application," in *Proc. IEEE Indian Conf. Antennas Propag. (InCAP)*, Dec. 2021, pp. 614–617.

[44] V. Palazzi, F. Alimenti, M. Virili, C. Mariotti, G. Orecchini, P. Mezzanotte, and L. Roselli, "A novel compact harmonic RFID sensor in paper substrate based on a variable attenuator and nested antennas," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2016, pp. 1–4.

[45] J. Bjorgaard, M. Hoyack, E. Huber, M. Mirzaee, Y.-H. Chang, and S. Noghanian, "Design and fabrication of antennas using 3D printing," *Prog. Electromagn. Res. C*, vol. 84, pp. 119–134, 2018.

[46] M. Mirzaee and Y. Kim, "A 3D-printed microwave passive sensor using fully biodegradable and renewable materials," in *Proc. United States Nat. Committee URSI Nat. Radio Sci. Meeting (USNC-URSI NRSM)*, Jan. 2022, pp. 82–83.

[47] H. Onyeaka, K. Obileke, G. Makaka, and N. Nwokolo, "Current research and applications of starch-based biodegradable films for food packaging," *Polymers*, vol. 14, no. 6, p. 1126, Mar. 2022.

[48] M. Mirzaee and S. Noghanian, "High frequency characterisation of wood-fill PLA for antenna additive manufacturing application," *Electron. Lett.*, vol. 52, no. 20, pp. 1656–1658, Sep. 2016.

[49] I. Ibanez Labiano and A. Alomainy, "Flexible inkjet-printed graphene antenna on kapton," *Flexible Printed Electron.*, vol. 6, no. 2, Jun. 2021, Art. no. 025010.

[50] M. E. de Cos Gómez, H. F. Álvarez, A. F. Berdasco, and F. L.-H. Andrés, "Paving the way to eco-friendly IoT antennas: Tencel-based ultra-thin compact monopole and its applications to ZigBee," *Sensors*, vol. 20, no. 13, p. 3658, Jun. 2020.

[51] P. Parthiban, B.-C. Seet, and X. J. Li, "Recycled polyolefin as dielectric substrate for patch antennas," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 26, no. 5, pp. 1720–1726, Oct. 2019.

[52] A. A. Benbuk, N. Kouzayha, J. Costantine, and Z. Dawy, "Charging and wake-up of IoT devices using harvested RF energy with near-zero power consumption," *IEEE Internet Things Mag.*, vol. 6, no. 1, pp. 162–167, Mar. 2023.

[53] P. Castillejo, J.-F. Martinez, J. Rodriguez-Molina, and A. Cuerva, "Integration of wearable devices in a wireless sensor network for an E-health application," *IEEE Wireless Commun.*, vol. 20, no. 4, pp. 38–49, Aug. 2013.

[54] S. Appusamy, S. Krishnan, M. Gopikrishna, and S. Raman, "Bio-based materials for microwave devices: A review," *J. Electron. Mater.*, vol. 50, no. 4, pp. 1893–1921, Feb. 2021.

[55] A. Verma, B. Weng, R. Shepherd, C. Fumeaux, V.-T. Truong, G. G. Wallace, and B. D. Bates, "6 GHz microstrip patch antennas with PEDOT and polypyrrole conducting polymers," in *Proc. Int. Conf. Electromagn. Adv. Appl.*, Sep. 2010, pp. 329–332.

[56] T. Kaufmann, A. Verma, V.-T. Truong, B. Weng, R. Shepherd, and C. Fumeaux, "Efficiency of a compact elliptical planar ultra-wideband antenna based on conductive polymers," *Int. J. Antennas Propag.*, vol. 2012, pp. 1–11, Jan. 2012.

[57] F. Alimenti, P. Mezzanotte, S. Giacomucci, M. Dionigi, C. Mariotti, M. Virili, and L. Roselli, "24 GHz single-balanced diode mixer exploiting cellulose-based materials," *IEEE Microw. Wireless Compon. Lett.*, vol. 23, no. 11, pp. 596–598, Nov. 2013.

[58] R. Gonçalves, S. Rima, R. Magueta, P. Pinho, A. Collado, A. Georgiadis, J. Hester, N. B. Carvalho, and M. M. Tentzeris, "RFID-based wireless passive sensors utilizing cork materials," *IEEE Sensors J.*, vol. 15, no. 12, pp. 7242–7251, Dec. 2015.

[59] A. Mostaccio, G. M. Bianco, G. Marrocco, and C. Occhiuzzi, "RFID technology for food Industry 4.0: A review of solutions and applications," *IEEE J. Radio Freq. Identificat.*, vol. 7, pp. 145–157, 2023.

[60] D. Jayawardana, S. Kharkovsky, R. Liyanapathirana, and X. Zhu, "Measurement system with accelerometer integrated RFID tag for infrastructure health monitoring," *IEEE Trans. Instrum. Meas.*, vol. 65, no. 5, pp. 1163–1171, May 2016.

[61] K. Guerchouche, E. Herth, L. E. Calvet, N. Roland, and C. Loyez, "Conductive polymer based antenna for wireless green sensors applications," *Microelectronic Eng.*, vol. 182, pp. 46–52, Oct. 2017.

[62] V. Palazzi, F. Alimenti, P. Mezzanotte, M. Virili, C. Mariotti, G. Orecchini, and L. Roselli, "Low-power frequency doubler in cellulose-based materials for harmonic RFID applications," *IEEE Microw. Wireless Compon. Lett.*, vol. 24, no. 12, pp. 896–898, Dec. 2014.

[63] A. Gunatilake, S. Kodagoda, and K. Thiyagarajan, "A novel UHF-RFID dual antenna signals combined with Gaussian process and particle filter for in-pipe robot localization," *IEEE Robot. Autom. Lett.*, vol. 7, no. 3, pp. 6005–6011, Jul. 2022.

[64] A. Gunatilake, S. Kodagoda, and K. Thiyagarajan, "Battery-free UHF-RFID sensors-based SLAM for in-pipe robot perception," *IEEE Sensors J.*, vol. 22, no. 20, pp. 20019–20026, Oct. 2022.

[65] V. Lakafosis, A. Rida, R. Vyas, L. Yang, S. Nikolaou, and M. M. Tentzeris, "Progress towards the first wireless sensor networks consisting of inkjet-printed, paper-based RFID-enabled sensor tags," *Proc. IEEE*, vol. 98, no. 9, pp. 1601–1609, Sep. 2010.

[66] A. Scidà, S. Haque, E. Treossi, A. Robinson, S. Smerzi, S. Ravesi, S. Borini, and V. Palermo, "Application of graphene-based flexible antennas in consumer electronic devices," *Mater. Today*, vol. 21, no. 3, pp. 223–230, Apr. 2018.

[67] C.-H. Yeh, Y.-W. Lain, Y.-C. Chiu, C.-H. Liao, D. R. Moyano, S. S. H. Hsu, and P.-W. Chiu, "Gigahertz flexible graphene transistors for microwave integrated circuits," *ACS Nano*, vol. 8, no. 8, pp. 7663–7670, Jul. 2014.

[68] P.-Y. Chen, C. Argyropoulos, and A. Alu, "Terahertz antenna phase shifters using integrally-gated graphene transmission-lines," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1528–1537, Apr. 2013.

[69] Y. Tan, M. M. Elahi, H.-Y. Tsao, K. M. M. Habib, N. S. Barker, and A. W. Ghosh, "Graphene Klein tunnel transistors for high speed analog RF applications," *Sci. Rep.*, vol. 7, no. 1, p. 9714, Aug. 2017.

[70] Y. H. Jung, T.-H. Chang, H. Zhang, C. Yao, Q. Zheng, V. W. Yang, H. Mi, M. Kim, S. J. Cho, D.-W. Park, H. Jiang, J. Lee, Y. Qiu, W. Zhou, Z. Cai, S. Gong, and Z. Ma, "High-performance green flexible electronics based on biodegradable cellulose nanofibril paper," *Nature Commun.*, vol. 6, no. 1, p. 7170, May 2015.

[71] A. Gunatilake, K. Thiyagarajan, and S. Kodagoda, "Evaluation of battery-free UHF-RFID sensor wireless signals for in-pipe robotic applications," in *Proc. IEEE Sensors*, Oct. 2021, pp. 1–4.

[72] S. Y. Yang, S. K. Mahadeva, and J. Kim, "Remotely powered and controlled EAPap actuator by amplitude modulated microwaves," *Smart Mater. Struct.*, vol. 22, no. 1, Dec. 2012, Art. no. 017001.

[73] K. Zeouga, L. Osman, A. Gharsallah, and B. Gupta, "Truncated patch antenna on jute textile for wireless power transmission at 2.45 GHz," *Int. J. Adv. Comput. Sci. Appl.*, vol. 9, no. 1, pp. 301–305, 2018.

[74] T. A. Elwi, "Novel UWB printed metamaterial microstrip antenna based organic substrates for RF-energy harvesting applications," *AEU-Int. J. Electron. Commun.*, vol. 101, pp. 44–53, Mar. 2019.

[75] Q. Guo, J. Koo, Z. Xie, R. Avila, X. Yu, X. Ning, H. Zhang, X. Liang, S. B. Kim, Y. Yan, M. R. MacEwan, H. M. Lee, A. Song, Z. Di, Y. Huang, Y. Mei, and J. A. Rogers, "A bioresorbable magnetically coupled system for low frequency wireless power transfer," *Adv. Funct. Mater.*, vol. 29, Sep. 2019, Art. no. 1905451.

[76] A. Rahman, M. T. Islam, M. J. Singh, S. Kibria, and M. Akhtaruzzaman, "Electromagnetic performances analysis of an ultra-wideband and flexible material antenna in microwave breast imaging: To implement a wearable medical bra," *Sci. Rep.*, vol. 6, no. 1, p. 38906, Dec. 2016.

[77] D. Tang, Q. Wang, Z. Wang, Q. Liu, B. Zhang, D. He, Z. Wu, and S. Mu, "Highly sensitive wearable sensor based on a flexible multi-layer graphene film antenna," *Sci. Bull.*, vol. 63, no. 9, pp. 574–579, May 2018.

[78] V. Palazzi, F. Alimenti, C. Kalialakis, P. Mezzanotte, A. Georgiadis, and L. Roselli, "Highly integrable paper-based harmonic transponder for low-power and long-range IoT applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 3196–3199, 2017.

[79] P. U. Linge, T. Gerges, P. Bevilacqua, J.-M. Duchamp, P. Benech, J. Verdier, P. Lombard, M. Cabrera, P. Tsafack, F. Mieyeville, and B. Allard, "Evaluation of polylactic acid polymer as a substrate in rectenna for ambient radiofrequency energy harvesting," *J. Low Power Electron. Appl.*, vol. 13, no. 2, p. 34, May 2023.

[80] D. D. Patil, K. S. Subramanian, and N. C. Pradhan, "3D-printed dual-band rectenna system for green IoT application," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 70, no. 8, pp. 2864–2868, Aug. 2023.

[81] M. Mirzaee and Y. Kim, "On the far-field characteristics of a 3D-printed antenna using wood-based PLA and conductive silver nanoparticle ink," in *Proc. United States Nat. Committee URSI Nat. Radio Sci. Meeting (USNC-URSI NRSM)*, Jan. 2022, pp. 76–77.

[82] A. Kumar and K. Karthick, "Properties of biodegradable polymers and degradation for sustainable development," *Int. J. Chem. Eng. Appl.*, vol. 2, no. 3, p. 164–167, Jun. 2011.

[83] X. Huang, Y. Liu, S. Hwang, S. Kang, D. Patnaik, J. F. Cortes, and J. A. Rogers, "Biodegradable materials for multilayer transient printed circuit boards," *Adv. Mater.*, vol. 26, no. 43, pp. 7371–7377, Sep. 2014.

[84] K. Unda, A. Mohammad-Khāh, K.-M. Lee, D. E. Day, M. J. O'Keefe, and C.-S. Kim, "Sensor substrates based on biodegradable glass materials," in *Proc. IEEE SENSORS*, Oct. 2016, pp. 1–3.

[85] M. Pandimadevi, R. Tamilselvi, and M. Parisa Beham, "Design and simulation of flexible jute antenna with performance validation on bending and soaking conditions," *Textile Res. J.*, vol. 91, nos. 1–2, pp. 219–231, Jun. 2020.

[86] E. Stegner, B. Thompson, L. Hibl, J. C. Reich, and C. Bauer-Reich, "Biodegradable deployment apparatus for environmentally-friendly RFID-based sensors," in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting (AP-S/URSI)*, Jul. 2022, pp. 113–114.

[87] K. W. Meereboer, M. Misra, and A. K. Mohanty, "Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their composites," *Green Chem.*, vol. 22, no. 17, pp. 5519–5558, 2020.
[88] M. T. Review. (Jul. 2015). *A Biodegradable Computer Chip That Performs Surprisingly Well*. Accessed: Jul. 2024. [Online]. Available: https://www.technologyreview.com/2015/07/14/167161/a-biodegradable-computer-chip-that-performs-surprisingly-well/
[89] N. A. Zulkifli, F. H. Wee, N. Mahrom, B. S. Yew, Y. S. Lee, S. Z. Ibrahim, and A. L. A. Phan, "Analysis of dielectric properties on agricultural waste for microwave communication application," in *Proc. MATEC Web Conf.*, vol. 140, 2017, p. 01013.
[90] T. Homsai, C. Phongcharoenpanich, and W. Sriseubsai, "Bio-degradable material realization for antenna fabrication in wireless communications," in *Proc. MATEC Web Conf.*, vol. 192, 2018, p. 01035.
[91] A. R. Eldamak and E. C. Fear, "Conformal and disposable antenna-based sensor for non-invasive sweat monitoring," *Sensors*, vol. 18, no. 12, p. 4088, Nov. 2018.
[92] S. Gopalakrishnan, J. Waimin, A. Zareei, S. Sedaghat, N. Raghunathan, A. Shakouri, and R. Rahimi, "A biodegradable chipless sensor for wireless subsoil health monitoring," *Sci. Rep.*, vol. 12, no. 1, p. 8011, May 2022.
[93] W. B. Han, J. H. Lee, J. Shin, and S. Hwang, "Advanced materials and systems for biodegradable, transient electronics," *Adv. Mater.*, vol. 32, no. 51, Sep. 2020, Art. no. 2002211.
[94] J. Min, Y. Jung, J. Ahn, J. G. Lee, J. Lee, and S. H. Ko, "Recent advances in biodegradable green electronic materials and sensor applications," *Adv. Mater.*, vol. 35, no. 52, Nov. 2023, Art. no. 2211273.
[95] K. A. M. Joy, M. Devaerakkam, D. G. Immanuel, K. N. Raghavan, G. K. Prince, and K. Negash, "Design and fabrication of biodegradable antenna using jute material for UWB application," *Adv. Mater. Sci. Eng.*, vol. 2022, pp. 1–10, Mar. 2022.
[96] S. Mamun, S. K. Shuvessa, A. Al Ryan, N. Nabi, and Md. S. Ahamed, "JuteBangla: A comparative study on jute yield prediction using supervised machine learning approach based on Bangladesh perspective," in *Proc. 13th Int. Conf. Comput. Commun. Netw. Technol. (ICCCNT)*, Oct. 2022, pp. 1–5.
[97] N. Zainol, N. Mustafa, N. H. Aziz, A. N. Azman, and M. S. A. Karim, "Dielectric materials development using bio-waste: A review," *J. Electr. Syst. Inf. Technol.*, vol. 10, no. 1, p. 47, Oct. 2023.
[98] S. N. S. Mahmud, M. A. Jusoh, K. Y. You, N. Salim, S. Shaheen, and A. G. E. Sutjipto, "Structural and dielectric properties of polyurethane palm oil based filled empty fruit bunch," *Int. J. Adv. Eng. Res. Sci.*, vol. 4, no. 1, pp. 259–264, 2017.
[99] (Nov. 2017). *Keysight Technologies Basics of Measuring the Dielectric Properties of Materials*. Accessed: Jul. 2024. [Online]. Available: https://www.keysight.com/au/en/assets/7018-01284/application-notes/5989-2589.pdf
[100] E. Huber, M. Mirzaee, J. Bjorgaard, M. Hoyack, S. Noghanian, and I. Chang, "Dielectric property measurement of PLA," in *Proc. IEEE Int. Conf. Electro Inf. Technol. (EIT)*, May 2016, pp. 0788–0792.
[101] M. Venkatesh and G. Raghavan, "An overview of dielectric properties measuring techniques," *Can. Biosyst. Eng.*, vol. 47, no. 7, pp. 15–30, 2005.
[102] M. Mirzaee and Y. Kim, "Toward fully biodegradable and renewable antennas using 3D printing technology," in *Proc. United States Nat. Committee URSI Nat. Radio Sci. Meeting (USNC-URSI NRSM)*, Jan. 2022, pp. 78–79.
[103] M. Mirzaee, S. Noghanian, and I. Chang, "Low-profile bowtie antenna with 3D printed substrate," *Microw. Opt. Technol. Lett.*, vol. 59, no. 3, pp. 706–710, Jan. 2017.
[104] G. K. F. Serres, R. R. C. S. Freire, S. M. A. Morais, C. C. R. Albuquerque, J. I. L. Araujo, A. J. R. Serres, L. H. de Carvalho, and J. N. Carvalho, "Eco-friendly metamaterial antenna for 2.4GHz WLAN applications," in *Proc. 14th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2020, pp. 1–5.
[105] A. Sid, P.-Y. Cresson, N. Joly, F. Braud, and T. Lasri, "A flexible and wearable dual band bio-based antenna for WBAN applications," *AEU-Int. J. Electron. Commun.*, vol. 157, Dec. 2022, Art. no. 154412.
[106] F. Alimenti, V. Palazzi, C. Mariotti, M. Virili, G. Orecchini, L. Roselli, and P. Mezzanotte, "24-GHz CW radar front-ends on cellulose-based substrates: A new technology for low-cost applications," in *IEEE MTT-S Int. Microw. Symp. Dig.*, May 2015, pp. 1–4.
[107] S. J. Chen, T. Kaufmann, R. Shepherd, B. Chivers, B. Weng, A. Vassallo, A. Minett, and C. Fumeaux, "A compact, highly efficient and flexible polymer ultra-wideband antenna," *IEEE Antennas Wireless Propag. Lett.*, vol. 14, pp. 1207–1210, 2015.
[108] M. Mirzaee and S. Noghanian, "3D printed antenna using biocompatible dielectric material and graphene," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2017, pp. 2543–2544.
[109] Y. Yamada, "Dielectric properties of textile materials: Analytical approximations and experimental measurements—A review," *Textiles*, vol. 2, no. 1, pp. 50–80, Jan. 2022.
[110] R. B. V. B. Simorangkir, Y. Yang, L. Matekovits, and K. P. Esselle, "Dual-band dual-mode textile antenna on PDMS substrate for body-centric communications," *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 677–680, 2017.
[111] J. Virtanen, J. Virkki, L. Sydänheimo, M. Tentzeris, and L. Ukkonen, "Automated identification of plywood using embedded inkjet-printed passive UHF RFID tags," *IEEE Trans. Autom. Sci. Eng.*, vol. 10, no. 3, pp. 796–806, Jul. 2013.
[112] Y. Bayram, Y. Zhou, B. S. Shim, S. Xu, J. Zhu, N. A. Kotov, and J. L. Volakis, "E-textile conductors and polymer composites for conformal lightweight antennas," *IEEE Trans. Antennas Propag.*, vol. 58, no. 8, pp. 2732–2736, Aug. 2010.
[113] S. Bashir, "Design and synthesis of non uniform high impedance surface based wearable antennas," Ph.D. thesis, School Mech., Elect. Manuf. Eng., Loughborough Univ., Loughborough, U.K., 2009.
[114] M. Mirzaee, S. Noghanian, L. Wiest, and I. Chang, "Developing flexible 3D printed antenna using conductive ABS materials," in *Proc. IEEE Int. Symp. Antennas Propag. USNC/URSI Nat. Radio Sci. Meeting*, Jul. 2015, pp. 1308–1309.
[115] A. Rida, L. Yang, R. Vyas, and M. M. Tentzeris, "Conductive inkjet-printed antennas on flexible low-cost paper-based substrates for RFID and WSN applications," *IEEE Antennas Propag. Mag.*, vol. 51, no. 3, pp. 13–23, Jun. 2009.
[116] S. Pranonsatit, D. Worasawate, and P. Sritanavut, "Affordable ink-jet printed antennas for RFID applications," *IEEE Trans. Compon., Packag., Manuf. Technol.*, vol. 2, no. 5, pp. 878–883, May 2012.
[117] A. R. Maza, B. Cook, G. Jabbour, and A. Shamim, "Paper-based inkjet-printed ultra-wideband fractal antennas," *IET Microw., Antennas Propag.*, vol. 6, no. 12, pp. 1366–1373, Sep. 2012.
[118] P. Mezzanotte, V. Palazzi, F. Alimenti, and L. Roselli, "Innovative RFID sensors for Internet of Things applications," *IEEE J. Microw.*, vol. 1, no. 1, pp. 55–65, Jan. 2021.
[119] C. L. Baumbauer, A. Gopalakrishnan, M. Atreya, G. L. Whiting, and A. C. Arias, "Polycaprolactone-based zinc ink for high conductivity transient printed electronics and antennas," *Adv. Electron. Mater.*, vol. 10, no. 4, Jan. 2024, Art. no. 2300658.
[120] C. T. Sandry, S. Shila, L. Gonzalez-Jimenez, S. Martinez, and P. Sekhar, "Progress in inkjet-printed sensors and antennas," *Electrochemical Soc. Interface*, vol. 32, no. 4, pp. 61–71, Dec. 2023.
[121] B. Cruz, A. Albrecht, P. Eschlwech, and E. Biebl, "Inkjet printing of metal nanoparticles for green UHF RFID tags," *Adv. Radio Sci.*, vol. 17, pp. 119–127, Sep. 2019.
[122] J. Li, J. Liu, W. Huo, J. Yu, X. Liu, M. J. Haslinger, M. Muehlberger, P. Kulha, and X. Huang, "Micro and nano materials and processing techniques for printed biodegradable electronics," *Mater. Today Nano*, vol. 18, Jun. 2022, Art. no. 100201.
[123] S. Agarwala, G. L. Goh, T.-S. Dinh Le, J. An, Z. K. Peh, W. Y. Yeong, and Y.-J. Kim, "Wearable bandage-based strain sensor for home healthcare: Combining 3D aerosol jet printing and laser sintering," *ACS Sensors*, vol. 4, no. 1, pp. 218–226, Dec. 2018.
[124] S. Agarwala and W. Y. Yeong, "Aerosol jet fabricated biodegradable antenna for bioelectronics application," *Trans. Additive Manuf. Meets Med.*, vol. 1, no. 1, Nov. 2019.
[125] L. Corchia, G. Monti, and L. Tarricone, "Wearable antennas: Nontextile versus fully textile solutions," *IEEE Antennas Propag. Mag.*, vol. 61, no. 2, pp. 71–83, Apr. 2019.
[126] J. Yeo, S. Moon, and J. Jung, "Antennas for a battery-assisted RFID tag with thin and flexible film batteries," *Microw. Opt. Technol. Lett.*, vol. 50, pp. 494–498, Dec. 2007.
[127] T. Starner, "Human-powered wearable computing," *IBM Syst. J.*, vol. 35, no. 3, pp. 618–629, 1996.

[128] M. M. H. Mahfuz, M. R. Islam, C.-W. Park, E. A. A. Elsheikh, F. M. Suliman, M. H. Habaebi, N. A. Malek, and N. Sakib, "Wearable textile patch antenna: Challenges and future directions," *IEEE Access*, vol. 10, pp. 38406–38427, 2022.

[129] M. Dulal, S. Afroj, J. Ahn, Y. Cho, C. Carr, I.-D. Kim, and N. Karim, "Toward sustainable wearable electronic textiles," *ACS Nano*, vol. 16, no. 12, pp. 19755–19788, Nov. 2022.

[130] O. Thompson, S. Alkaraki, Q. H. Abbasi, S. F. Jilani, and D. A. Evans, "A bio-degradable textile-based graphene antenna for the 5G smart wearables," in *Proc. 16th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2022, pp. 1–4.

[131] G. Tarabella, D. Vurro, S. Lai, P. D'Angelo, L. Ascari, and S. Iannotta, "Aerosol jet printing of PEDOT: PSS for large area flexible electronics," *Flexible Printed Electron.*, vol. 5, no. 1, Jan. 2020, Art. no. 014005.

[132] A. Mahajan, C. D. Frisbie, and L. F. Francis, "Optimization of aerosol jet printing for high-resolution, high-aspect ratio silver lines," *ACS Appl. Mater. Interfaces*, vol. 5, no. 11, pp. 4856–4864, May 2013.

[133] A. Német, S. Alkaraki, Q. H. Abassi, and S. F. Jilani, "A biodegradable textile-based graphene antenna for 5G wearable applications," in *Proc. IEEE Int. Symp. Antennas Propag. USNC-URSI Radio Sci. Meeting (APS/URSI)*, Dec. 2021, pp. 1583–1584.

[134] V. Palazzi, S. Bonafoni, F. Alimenti, P. Mezzanotte, and L. Roselli, "Feeding the world with microwaves: How remote and wireless sensing can help precision agriculture," *IEEE Microw. Mag.*, vol. 20, no. 12, pp. 72–86, Dec. 2019.

[135] S.-N. Daskalakis, S. D. Assimonis, E. Kampianakis, and A. Bletsas, "Soil moisture scatter radio networking with low power," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 7, pp. 2338–2346, Jul. 2016.

[136] A. Bilir and S. Dumanli, "Biodegradable implant antenna utilized for real-time sensing through genetically modified bacteria," in *Proc. 18th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2024, pp. 1–4.

[137] U. Ali, S. Ullah, B. Kamal, L. Matekovits, and A. Altaf, "Design, analysis and applications of wearable antennas: A review," *IEEE Access*, vol. 11, pp. 14458–14486, 2023.

[138] J. Botero-valencia, L. Castano-Londono, D. Marquez-Viloria, and M. Rico-Garcia, "Data reduction in a low-cost environmental monitoring system based on Lora for WSN," *IEEE Internet Things J.*, vol. 6, no. 2, pp. 3024–3030, Apr. 2019.

[139] P. R. Salgado, L. Di Giorgio, Y. S. Musso, and A. N. Mauri, "Recent developments in smart food packaging focused on biobased and biodegradable polymers," *Frontiers Sustain. Food Syst.*, vol. 5, Apr. 2021, Art. no. 630393.

[140] M. Institute. *Biodegradable Electronic Devices for Wildlife Conservation and Lifestock Management Thanks To Clever Proteins—Macdiarmid*. Accessed: Jun. 13, 2024. [Online]. Available: https://www.macdiarmid.ac.nz/news-and-events/news/annual-reports-pages/biodegradable-electronic-devices-for-wildlife-conservation-and-lifestock-management-thanks-to-clever-proteins/

[141] Y. Mehmood, F. Ahmad, I. Yaqoob, A. Adnane, M. Imran, and S. Guizani, "Internet-of-Things-based smart cities: Recent advances and challenges," *IEEE Commun. Mag.*, vol. 55, no. 9, pp. 16–24, Sep. 2017.

[142] M. Wagih, N. Hillier, S. Yong, A. S. Weddell, and S. Beeby, "RF-powered wearable energy harvesting and storage module based on E-textile coplanar waveguide rectenna and supercapacitor," *IEEE Open J. Antennas Propag.*, vol. 2, pp. 302–314, 2021.

[143] M. Wagih, A. Komolafe, and N. Hillier, "Screen-printable flexible textile-based ultra-broadband millimeter-wave DC-blocking transmission lines based on microstrip-embedded printed capacitors," *IEEE J. Microw.*, vol. 2, no. 1, pp. 162–173, Jan. 2022.

[144] S. Lemey, S. Agneessens, P. Van Torre, K. Baes, J. Vanfleteren, and H. Rogier, "Wearable flexible lightweight modular RFID tag with integrated energy harvester," *IEEE Trans. Microw. Theory Techn.*, vol. 64, no. 7, pp. 2304–2314, Jul. 2016.

[145] S. Hwang, X. Huang, J. Seo, J. Song, S. Kim, S. Hage-Ali, H. Chung, H. Tao, F. G. Omenetto, Z. Ma, and J. A. Rogers, "Materials for bioresorbable radio frequency electronics," *Adv. Mater.*, vol. 25, no. 26, pp. 3526–3531, May 2013.

[146] C. Hoyer, L. Steinweg, Z. Cao, V. Rieß, L. Li, F. Protze, C. Carta, J. Wagner, M. Kaynak, B. Tillack, and F. Ellinger, "Bendable 190-GHz transmitter on 20-μm ultra-thin SiGe BiCMOS," *IEEE J. Flexible Electron.*, vol. 1, no. 2, pp. 122–133, Apr. 2022.

[147] M. Wagih, S. Yong, K. Yang, A. S. Weddell, and S. Beeby, "Printed non-metallic textile-based carbon antenna for low-cost green wearable applications," in *Proc. 16th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2022, pp. 1–4.

[148] S. C. Teixeira, N. O. Gomes, M. L. Calegaro, S. A. S. Machado, T. V. de Oliveira, N. de F. F. Soares, and P. A. Raymundo-Pereira, "Sustainable plant-wearable sensors for on-site, rapid decentralized detection of pesticides toward precision agriculture and food safety," *Biomaterials Adv.*, vol. 155, Dec. 2023, Art. no. 213676.

[149] A.-M. Zaccarin, G. M. Iyer, R. H. Olsson, and K. T. Turner, "Fabrication and characterization of soil moisture sensors on a biodegradable, cellulose-based substrate," *IEEE Sensors J.*, vol. 24, no. 6, pp. 7235–7243, Mar. 2024.

[150] V. Palazzi, F. Gelati, U. Vaglioni, F. Alimenti, P. Mezzanotte, and L. Roselli, "Leaf-compatible autonomous RFID-based wireless temperature sensors for precision agriculture," in *Proc. IEEE Topical Conf. Wireless Sensors Sensor Netw. (WiSNet)*, Jan. 2019, pp. 1–4.

[151] S. S. Sethi, M. Kovac, F. Wiesemüller, A. Miriyev, and C. M. Boutry, "Biodegradable sensors are ready to transform autonomous ecological monitoring," *Nature Ecol. Evol.*, vol. 6, no. 9, pp. 1245–1247, Jul. 2022.

[152] T. Athauda and N. C. Karmakar, "The realization of chipless RFID resonator for multiple physical parameter sensing," *IEEE Internet Things J.*, vol. 6, no. 3, pp. 5387–5396, Jun. 2019.

[153] J. Bourely, L. De Sousa, N. Fumeaux, O. Vorobyov, C. Beyer, and D. Briand, "Biodegradable materials as sensitive coatings for humidity sensing in S-band microwave frequencies," *Micro Nano Eng.*, vol. 19, Jun. 2023, Art. no. 100185.

[154] R. Salama and S. Kharkovsky, "An embeddable microwave patch antenna module for civil engineering applications," in *Proc. IEEE Int. Instrum. Meas. Technol. Conf. (IMTC)*, May 2013, pp. 27–30.

[155] X. Aeby, J. Bourely, A. Poulin, G. Siqueira, G. Nyström, and D. Briand, "Printed humidity sensors from renewable and biodegradable materials," *Adv. Mater. Technol.*, vol. 8, no. 5, Nov. 2022, Art. no. 2201302.

[156] G. A. Salvatore, J. Sülzle, F. Dalla Valle, G. Cantarella, F. Robotti, P. Jokic, S. Knobelspies, A. Daus, L. Büthe, L. Petti, N. Kirchgessner, R. Hopf, M. Magno, and G. Tröster, "Biodegradable and highly deformable temperature sensors for the Internet of Things," *Adv. Funct. Mater.*, vol. 27, no. 35, Jul. 2017, Art. no. 1702390.

[157] N. Ashammakhi, A. L. Hernandez, B. D. Unluturk, S. A. Quintero, N. R. de Barros, E. Hoque Apu, A. Bin Shams, S. Ostrovidov, J. Li, C. Contag, A. S. Gomes, and M. Holgado, "Biodegradable implantable sensors: Materials design, fabrication, and applications," *Adv. Funct. Mater.*, vol. 31, no. 49, Aug. 2021, Art. no. 2104149.

[158] E. S. Hosseini, S. Dervin, P. Ganguly, and R. Dahiya, "Biodegradable materials for sustainable health monitoring devices," *ACS Appl. Bio Mater.*, vol. 4, no. 1, pp. 163–194, Dec. 2020.

[159] P. Sen, S. N. R. Kantareddy, R. Bhattacharyya, S. E. Sarma, and J. E. Siegel, "Low-cost diaper wetness detection using hydrogel-based RFID tags," *IEEE Sensors J.*, vol. 20, no. 6, pp. 3293–3302, Mar. 2020.

[160] M. Luo, A. W. Martinez, C. Song, F. Herrault, and M. G. Allen, "A microfabricated wireless RF pressure sensor made completely of biodegradable materials," *J. Microelectromech. Syst.*, vol. 23, no. 1, pp. 4–13, Feb. 2014.

[161] S. Yan, P. J. Soh, and G. A. E. Vandenbosch, "Wearable ultrawideband technology—A review of ultrawideband antennas, propagation channels, and applications in wireless body area networks," *IEEE Access*, vol. 6, pp. 42177–42185, 2018.

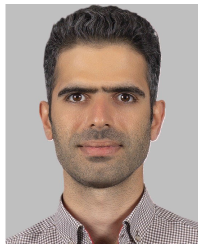
[162] K. N. Paracha, S. K. Abdul Rahim, P. J. Soh, and M. Khalily, "Wearable antennas: A review of materials, structures, and innovative features for autonomous communication and sensing," *IEEE Access*, vol. 7, pp. 56694–56712, 2019.

[163] M. A. A. Mamun and M. R. Yuce, "Sensors and systems for wearable environmental monitoring toward IoT-enabled applications: A review," *IEEE Sensors J.*, vol. 19, no. 18, pp. 7771–7788, Sep. 2019.

[164] T. A. Baldo, L. F. de Lima, L. F. Mendes, W. R. de Araujo, T. R. L. C. Paixão, and W. K. T. Coltro, "Wearable and biodegradable sensors for clinical and environmental applications," *ACS Appl. Electron. Mater.*, vol. 3, no. 1, pp. 68–100, Dec. 2020.

[165] Z. Li, S. K. Sinha, G. M. Treich, Y. Wang, Q. Yang, A. A. Deshmukh, G. A. Sotzing, and Y. Cao, "All-organic flexible fabric antenna for wearable electronics," *J. Mater. Chem. C*, vol. 8, no. 17, pp. 5662–5667, 2020.

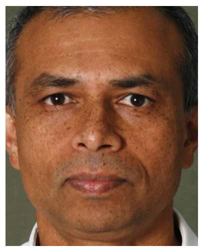
[166] D. Ziani, M. Belkheir, A. Mokaddem, and M. Rouissat, "Enhancing circular microstrip antenna performance with polydimethylsiloxane (PDMS) and polymethyl methacrylate (PMMA) substrates in sub-6 GHz: A comparative study," *Int. J. Interact. Design Manuf. (IJIDeM)*, vol. 18, no. 7, pp. 5109–5120, Oct. 2023.
[167] J. Wang, J. Zhuang, W. Jin, Q. Yu, J. Yu, L. He, Q. Wang, D. Cheng, G. Cai, and X. Wang, "Liquid metal-based on cotton/lycra elastic fabric surface for flexible antenna and wearable strain sensor," *Cellulose*, vol. 30, no. 17, pp. 11261–11272, Oct. 2023.
[168] I. Marasco, G. Niro, G. de Marzo, F. Rizzi, A. D'Orazio, M. Grande, and M. De Vittorio, "Design and fabrication of a plastic-free antenna on a sustainable chitosan substrate," *IEEE Electron Device Lett.*, vol. 44, no. 2, pp. 341–344, Feb. 2023.
[169] D. Ziani, M. Belkheir, M. Rouissat, A. Mokaddem, I. S. Alsukayti, and S. B. Belhouari, "Design optimization for enhancing microstrip antenna performances using polylactic acid (PLA) biopolymer substrate in sub-6 GHz band," *Int. J. Precis. Eng. Manuf.*, vol. 25, no. 7, pp. 1425–1436, Apr. 2024.
[170] A. Krishnan, K. Thiyagarajan, S. Kodagoda, and M. Bhattacharjee, "Wearable flexible temperature sensor suite for thermal tactile perception," *IEEE Sensors J.*, vol. 24, no. 23, pp. 39736–39743, Oct. 2024.
[171] A. Krishnan, K. Thiyagarajan, M. Bhattacharjee, and Y. An, "Performance evaluation of a skin conformable polymer-based flexible temperature sensor," in *Proc. IEEE Sensors*, Kobe, Japan, Oct. 2024, pp. 1–4.
[172] Y. Jung, J. Min, J. Choi, J. Bang, S. Jeong, K. R. Pyun, J. Ahn, Y. Cho, S. Hong, S. Hong, J. Lee, and S. H. Ko, "Smart paper electronics by laser-induced graphene for biodegradable real-time food spoilage monitoring," *Appl. Mater. Today*, vol. 29, Dec. 2022, Art. no. 101589.
[173] X. Chen, R. Zhang, Z. Wan, Z. Wu, D. Song, and X. Xiao, "Laser-induced graphene based flexible sensing and heating for food monitoring," *ACS Appl. Electron. Mater.*, vol. 6, no. 5, pp. 3597–3609, Apr. 2024.
[174] M. Mohammadifar and S. Choi, "A solid phase bacteria-powered biobattery for low-power, low-cost, Internet of Disposable Things," *J. Power Sources*, vol. 429, pp. 105–110, Jul. 2019.
[175] V. P. Singh, K. Krishnamoorthy, and M. R. Rahman, "Graphene-oxide-coated flexible fabric antenna sensor for contact-free H_2O sensing," *IEEE Sensors J.*, vol. 24, no. 2, pp. 1175–1182, Jan. 2024.
[176] H. Tao, M. A. Brenckle, M. Yang, J. Zhang, M. Liu, S. M. Siebert, R. D. Averitt, M. S. Mannoor, M. C. McAlpine, J. A. Rogers, D. L. Kaplan, and F. G. Omenetto, "Silk based conformal, adhesive, edible food sensors," *Adv. Mater.*, vol. 24, pp. 1067–1072, Jan. 2012.
[177] A. Abdelnour, F. Buchin, D. Kaddour, and S. Tedjini, "Improved traceability solution based on UHF RFID for cheese production sector," *IEEE J. Radio Freq. Identificat.*, vol. 2, no. 2, pp. 68–72, Jun. 2018.
[178] S. Das, M. Bhattacharjee, K. Thiyagarajan, and S. Kodagoda, "Conformable packaging of a soft pressure sensor for tactile perception," *Flexible Printed Electron.*, vol. 8, no. 3, Aug. 2023, Art. no. 035006.
[179] S. Das, M. Bhattacharjee, K. Thiyagarajan, and S. Kodagoda, "Nonlinear response analysis of a polymer-based piezoresistive flexible tactile sensor at low pressure," *IEEE Sensors Lett.*, vol. 7, no. 11, pp. 1–4, Nov. 2023.
[180] R. Storn and K. Price, "Differential evolution—A simple and efficient heuristic for global optimization over continuous spaces," *J. Global Optim.*, vol. 11, no. 4, pp. 341–359, 1997.
[181] J. H. Holland, "Genetic algorithms," *Sci. Amer.*, vol. 267, no. 1, pp. 66–72, Jul. 1992.
[182] M. Ghasemi, M. Zare, A. Zahedi, M.-A. Akbari, S. Mirjalili, and L. Abualigah, "Geyser inspired algorithm: A new geological-inspired meta-heuristic for real-parameter and constrained engineering optimization," *J. Bionic Eng.*, vol. 21, no. 1, pp. 374–408, Sep. 2023.
[183] M. Ghasemi, M. Zare, A. Zahedi, P. Trojovský, L. Abualigah, and E. Trojovská, "Optimization based on performance of lungs in body: Lungs performance-based optimization (LPO)," *Comput. Methods Appl. Mech. Eng.*, vol. 419, Feb. 2024, Art. no. 116582.
[184] S. Karimkashi and A. A. Kishk, "Invasive weed optimization and its features in electromagnetics," *IEEE Trans. Antennas Propag.*, vol. 58, no. 4, pp. 1269–1278, Apr. 2010.
[185] S. Mirjalili, S. M. Mirjalili, and A. Lewis, "Grey wolf optimizer," *Adv. Eng. Softw.*, vol. 69, pp. 46–61, Jan. 2014.
[186] X.-S. Yang, *Firefly Algorithms for Multimodal Optimization*. Berlin, Germany: Springer, 2009, pp. 169–178.
[187] M. Zare, M. Ghasemi, A. Zahedi, K. Golalipour, S. K. Mohammadi, S. Mirjalili, and L. Abualigah, "A global best-guided firefly algorithm for engineering problems," *J. Bionic Eng.*, vol. 20, no. 5, pp. 2359–2388, May 2023.
[188] S. Kirkpatrick, C. D. Gelatt, and M. P. Vecchi, "Optimization by simulated annealing," *Science*, vol. 220, no. 4598, pp. 671–680, May 1983.
[189] E. Rashedi, H. Nezamabadi-Pour, and S. Saryazdi, "GSA: A gravitational search algorithm," *Inf. Sci.*, vol. 179, no. 13, pp. 2232–2248, Jun. 2009.



AMIR ZAHEDI (Graduate Student Member, IEEE) received the M.Sc. degree in telecommunications engineering from Tarbiat Modares University, Tehran, Iran, in 2015. He is currently pursuing the Ph.D. degree with the School of Engineering, Design and Built Environment, Western Sydney University, Sydney, Australia.

From 2015 to 2019, he was a Research Assistant with the Antenna Laboratory, Tarbiat Modares University. He also gained industry experience at MTNIrancell Labs, from 2020 to 2023, working as a 4G/LTE Senior Specialist and a PMO Manager. He is currently the IEEE Student Branch Chair with Western Sydney University. His current research interests include biodegradable and renewable antennas and sensors, RF and microwave circuits, and optimization methods applied to engineering problems.

Mr. Zahedi has previously contributed to the Student Activities, Membership Development, and Young Professionals Committees in the IEEE Iran Section, from 2014 to 2019.



RANJITH LIYANAPATHIRANA (Life Senior Member, IEEE) received the B.Sc.Eng. degree (Hons.) in electronic and telecommunication engineering from the University of Moratuwa, Sri Lanka, and the Ph.D. degree in electrical engineering from Memorial University, Newfoundland, Canada.

He is currently a Senior Lecturer with the School of Engineering, Design and Built Environment, Western Sydney University, Australia. He has published over 150 papers in peer-reviewed journals and conferences. His current research interests include wireless sensor networks, biomedical engineering, infrastructure health monitoring, and engineering education.

Dr. Liyanapathirana is a fellow of the Institution of Engineers (FIEAust) and a Senior Member of the Australian Computer Society.

KARTHICK THIYAGARAJAN (Senior Member, IEEE) received the B.E. degree in electronics and instrumentation engineering from Anna University, Chennai, India, in 2011, the M.Sc. degree in mechatronics from Newcastle University, Newcastle upon Tyne, U.K., in 2013, and the Ph.D. degree in smart sensing from the University of Technology Sydney (UTS), Sydney, Australia, in 2018.

He is currently a Lecturer in mechatronic and robotic engineering, the Director of the Smart Sensing and Robotics (SensR) Laboratory, an Assistant Stream Leader in automation and robotics with the Centre for Advanced Manufacturing Technology, and a Subject Coordinator for several mechatronics and robotics subjects with Western Sydney University. His research interests include smart sensing, field robotics, assistive robotics and technology, and manufacturing robotics.

Dr. Thiyagarajan is an Executive Committee Member of the IEEE Sensors Council Young Professionals and Publicity Committee (2022–2024). He is the Secretary (2022–2024) of the IEEE Sensors Council NSW Chapter.