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Review

Applications of Nanomaterials in RFID Wireless Sensor Components

Sojeong Roh †, Trong Danh Nguyen † and Jun Seop Lee *

Department of Materials Science and Engineering, Gachon University, 1342 Seongnam-Daero, Sujeong-Gu, Gyeonggi-Do, Seongnam-Si 13120, Republic of Korea; hihithwjd@gachon.ac.kr (S.R.); ntdanh041@gachon.ac.kr (T.D.N.)
* Correspondence: junseop@gachon.ac.kr; Tel.: +82-31-750-5814
† These authors contributed equally to this work.

Abstract: Radio Frequency Identification (RFID) technology, capable of wirelessly processing large amounts of information, is gaining attention with the advancement of IoT technology. RFID systems can be utilized as Wireless Sensor Network (WSN) technology by introducing sensing materials responsive to external environmental stimuli. To achieve effective information communication and sensing capabilities, various types of nanomaterials are being used as various components of RFID sensors. This paper provides an overview of the RFID sensor system and the nanomaterials used in their composition. Polymers that can achieve flexibility are attracting more attention as user-friendly substrates as demand for them increases in the wearable market. Additionally, advancements in inkjet printing technology, allowing cost-effective and simple production of components, introduce inks and manufacturing methods utilizing various nanomaterials such as metal nanoparticles, carbon materials, and composites. Furthermore, nanomaterials utilized as sensing materials enable the detection of various external environments with high sensitivity and a wide detection range. Consequently, RFID sensor systems that achieve wireless detection in a variety of environments are actively utilized in many applications. By analyzing the current research progress and problems faced in RFID sensor technology, this paper suggests future research directions for its development as a next-generation wireless sensor system.

Keywords: wireless communication; Radio Frequency Identification (RFID); nanomaterials; sensor systems

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1. Introduction

Wireless communication technology facilitates the exchange of information between distributed points without the need for physical lines or direct plug-ins. With the rapid expansion of the Internet of Things (IoT), the integration of sensors and communication functions into various objects for internet connectivity has gained increased significance [1–5]. Wireless Sensor Network (WSN) is a specific type of wireless communication technology that collaboratively exchanges data by centrally collecting spatially distributed monitoring records [6–8]. WSN establishes a network structure by gathering data from sensor nodes and transmitting them externally to sink nodes [9,10].

Radio Frequency Identification (RFID), a subset of WSN technologies, enables the real-time collection and processing of information using radio frequency waves as a communication medium [11–15]. RFID is extensively employed in everyday life and industry due to its notable attributes such as high data throughput, contactless recognition, and data readability from multiple directions [16–23]. Notably, ongoing research is exploring the establishment of a wireless sensor network based on RFID communication methods capable of Wireless Information and Power Transfer (WIPT), with applications to various sensor devices [24–26].

Nanomaterials, characterized by a high surface area for chemical reactions and a unique surface structure that facilitates the implementation of flexible elements, enhance the superior performance and efficiency of RFID sensors [27–30]. Thoughtful material selection and the exploration of diverse structures contribute to the sensor's heightened reliability, selectivity, and rapid response and recovery performance to external stimuli [31–35]. Utilizing various materials in the fabrication of RFID sensor components allows for the effective integration of RFID wireless communication technology and sensing capabilities [36–40].

This review assesses the impact of applying various nanomaterials to RFID systems on wireless sensor performance, summarizing their contributions. Additionally, it introduces the fundamental mechanisms based on the configuration of RFID sensor systems and changes in electrical resistance. The review explores research trends related to various materials such as polymers, metal nanoparticles, and carbon-based materials applied to each component. Finally, an analysis of RFID sensor systems applied in diverse fields aims to predict the applicability and prospects of next-generation wireless sensors.

2. RFID System

Radio Frequency Identification (RFID) is a type of contactless wireless communication technology that utilizes radio waves as a transmission medium [41–43]. It consists of three components: tags, RFID readers, and IT systems (Figure 1). Tags, which contain unique information, record data through an integrated circuit chip (IC chip) and transmit and receive wireless signals via an antenna [44,45]. The wireless interaction between tags and RFID readers is based on digital or backscattered modulation, which involves altering the amplitude, phase, and frequency of radio waves [46]. Specifically, when a tag exists within the permissible range of a RFID reader, the tag receives the transmitted signal from the reader, modifies it, and sends it back as a modulated reflected signal through the antenna. The RFID reader converts the returned signal into digital format, decodes the embedded information, and transmits it to IT systems. Ultimately, IT systems collect data from distributed readers, manage information, and control the overall system.

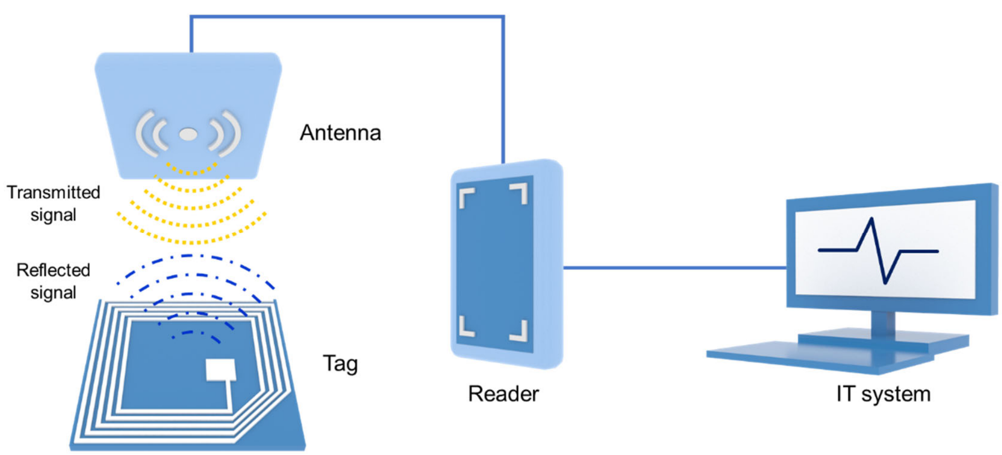

Figure 1. Radio Frequency Identification (RFID) device composed of three components: Tag, RFID reader and IT system.

Compared to traditional barcode recognition systems, RFID systems can process relatively large amounts of data over long distances due to their reliance on radio waves [21]. Additionally, RFID does not require direct or physical patterns, enabling recognition regardless of vertical or horizontal arrangements. Consequently, RFID can capture signals over a wide range and in all directions without direct contact. Furthermore, using electronic circuits (IC chips) instead of visual pattern arrays allows RFID to store more information than barcodes [47].

The operating frequency range of the tag is broadly categorized into three ranges, determining the communication method and antenna type with the RFID reader (Figure 2a). For low operating frequencies, specifically in the range of 120–140 kHz (LF), the tag and RFID reader operate through inductive coupling, with the antenna used adopting a coil shape. In the case of an operating frequency of 13.56 MHz (HF), the tag and RFID reader operate through inductive or capacitive coupling, and the antenna used primarily employs a planar inductor [48,49]. In a high operating frequency range of 868–962 MHz (UHF), the tag and RFID reader are radiatively coupled according to the backscattering principle, and the antenna used in this case is either a dipole or microstrip [50].

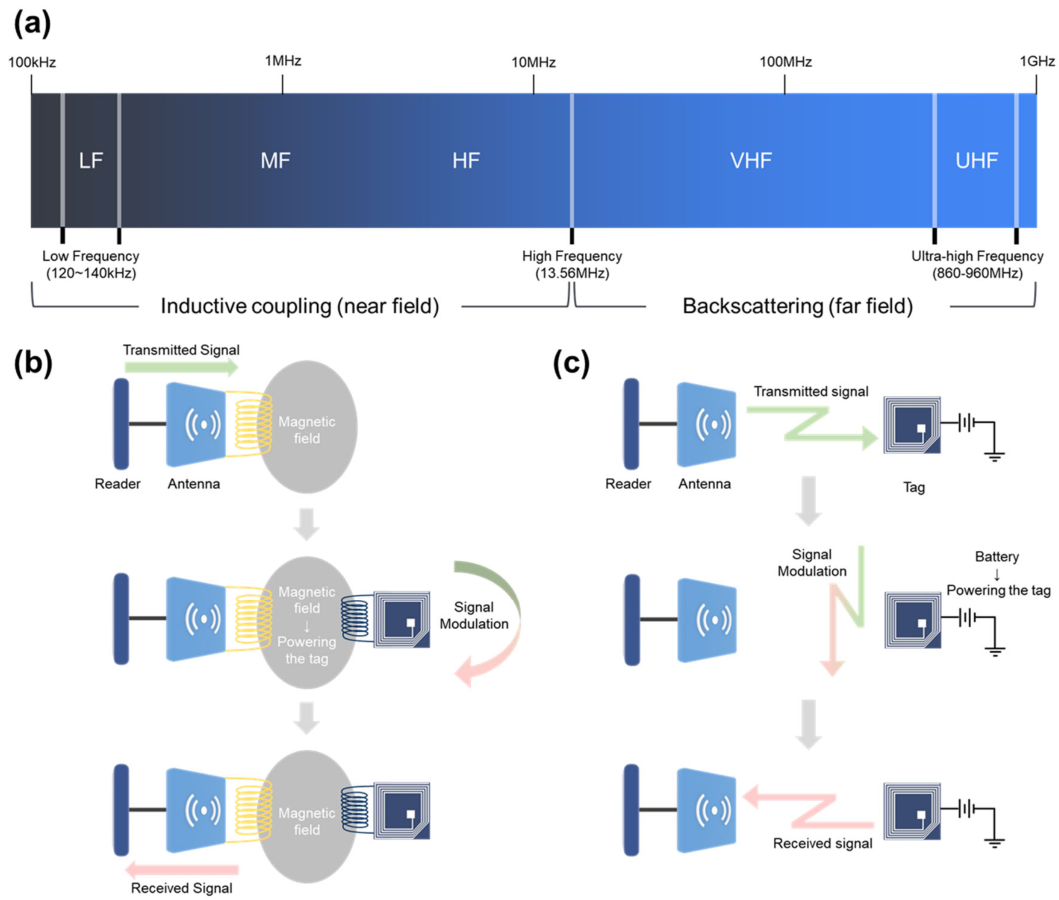

Figure 2. (**a**) Classification by radio frequency range. Operating procedures of (**b**) inductive coupling-based and (**c**) backscattering-based RFIDs.

3. RFID Sensor Technology

The principles of systems operating through inductive coupling, such as LF and HF, are as follows (Figure 2b) [51]. The process initiates by creating a magnetic field in the RFID reader antenna through a driving current. When the tag is positioned in the corresponding magnetic field region, current is induced, resulting in the generation of voltage, ultimately activating the RFID system. The signal transmitted from the reader is modified by the unique pattern of the tag, and the reader decodes this information through demodulation. In this case, since the current flowing through the tag is very weak, only short-range transmission is possible. Nevertheless, it exhibits less sensitivity to interference, allowing signals to be transmitted and received through objects such as metals or liquids [52]. LF RFID is effectively used in underground object detection such as mines, military munitions management, and urban construction tasks like subterranean manholes [53–

56]. HF RFID, with its relatively higher frequency, achieves improved reading range and processing speed, making it suitable for applications that require a slightly longer distance, such as library management, animal identification, and cold chain tracking [57–59].

On the other hand, in scenarios operating through backscattering, such as UHF, the RFID reader transmits an electric field signal to the tag to initiate the process (Figure 2c) [60]. The tag, activated by the signal from the RFID reader, conveys its information to the reflected signal by altering the RFID reader's radio signal. Subsequently, the RFID reader processes the information by recognizing the difference between the transmitted and received information. RFID, utilizing radio signals and receiving energy from its own battery, can continuously transmit and receive signals over much longer distances. In modern society, where there is a growing demand for automation and remote monitoring, the interest in UHF RFID applications, which offer a wide reading range and enable rapid data processing, continues to rise. UHF RFID, well suited for large-scale inventory management, is used in various fields such as supply chain management of large supermarkets, farm machinery, and automatic machine identification [61–63]. However, this outstanding performance not only increases the price but also increases the size and shortens the lifespan. Therefore, for effective RFID utilization, understanding the usage environment and necessary conditions is crucial, necessitating optimized design considerations.

Research on utilizing active substances with specific sensing capabilities for materials in RFID system tags to construct sensing tags and employ them as wireless sensors is being actively conducted. As shown in Figure 3a, a wireless sensor using a RFID system consists of a substrate, IC chip, sensing area, and antenna [64].

The operational principle of RFID-based wireless sensors involves a sensing tag, which carries the detection material, modulating and reflecting the signal transmitted by the RFID reader to interpret the reflected signal and acquire detection information (Figure 3b). Specifically, the RFID reader initiates the operation by transmitting the initial signal, P1, to the sensing tag. The sensing tag receives P1, and the detection area, occupying a small portion within the sensing tag, detects external stimuli. The detection area reacts to chemical environmental changes, causing a resistance change in the detection material. This change leads to alterations in reception signal parameters such as amplitude, frequency, and phase within the sensing tag. The modified reflected signal, P2, resulting from the material detection, is backscattered from the sensing tag to the RFID reader. Particularly, by analyzing the degree of change in the modulated P2 signal received by the RFID reader, one can calculate the quantity of the detected material. The reflected signal information read by the RFID reader is transmitted to the server via wireless communication methods, enabling users to utilize the collected information [65].

The substrate serves as the foundational material supporting various elements in constructing a sensing tag. It determines aspects such as the tag's size, shape, and strength, providing the mechanical structure for the sensing tag. The selection of the substrate must accommodate all components of the sensing tag without affecting the operating principles and antenna design frequencies. Substrates can be chosen from a variety of materials, including metal, ceramic, textile, plastic, and more [66–68]. Recently, attempts have been made to develop RFID yarns that can be immediately integrated into tag manufacturing, considering the widespread use of RFID in the clothing market. Additionally, there is growing attention to substrates that can provide flexibility and stretchability, especially with increasing demand for wearables (Figure 3c) [69]. The flexibility of the substrate allows it to withstand external mechanical impacts and makes it more suitable for attachment to the human biome. Stretchability, based on high elasticity and reversibility, demands properties that do not deform even with repeated strain and release. Research on flexible and stretchable RFID substrates is ongoing, with expectations that it will lead to various applications.

The Integrated Circuit (IC chip) is responsible for storing tag information and processing data. Sensing tags are distinguished based on the presence of the IC chip [70]. A sensing tag with an attached IC chip follows a conventional structure, where the IC chip not only handles the ID, data, and encryption key storage and processing but also includes digital logic required for data processing (Figure 3d) [71]. Such sensing tags allow for long-distance data reading and complex data processing. However, due to the inclusion of semiconductor-based IC chips, the manufacturing cost is higher. To address the need for more affordable and simpler sensing tags, a structure without the necessity of an IC chip has emerged. In cases where there is no IC chip, integrated patterns made of materials such as metal nanoparticles, conductive polymer inks, carbon materials, etc., serve as substitutes for IC chips [72–74]. Patterns replacing IC chips can be designed using various methods such as ultra-wide band (UWB), polarization diversity, phase quantization encoding, etc. [75–77]. This structure is cost-effective, has a long lifespan, and is suitable for use in harsh environments [78]. However, compared to cases with IC chips, sensitivity and selectivity are limited, requiring further research [79].

A certain portion of the sensing tag is configured as a sensing area using active substances to induce changes in the properties of the active substances in response to external physical or chemical stimuli (Figure 3e) [80]. Specifically, materials such as PEDOT, which changes in electrical conductivity based on pH, phenanthrene with a discontinuous dielectric constant above a certain temperature, and CNT, which alters resistance upon gas molecule adsorption, fall into this category [81–83]. The changes in the properties of the active substances result in impedance variations in the sensing tag, and the detection process is completed as the RFID reader detects these changes. This sensing area can detect various elements such as light, moisture, and temperature, making it applicable to diverse fields such as environmental monitoring, healthcare, agriculture, and food [84–86]. The integration of the sensing area into RFID sensor systems is achieved through various methods, including coating the antenna with active substances, attaching it across the antenna and IC chip, and inserting the sensing area by perforating holes in the antenna [87–90]. When designing the sensing area, it is crucial to select materials with high sensitivity to the target substance and to exercise caution to avoid influencing other components simultaneously.

In a RFID sensor system, the antenna is responsible for the data transmission and reception between the tag and the reader (Figure 3f) [91]. As detection occurs, the impedance matching between the antenna and chip of the tag changes, consequently altering the communication characteristics between the sensing tag and the RFID reader. The antenna serves as a mediator by transmitting and receiving the corresponding radio waves, enabling the identification of external stimuli. When designing the antenna, it is crucial to consider factors such as operating frequency, coupling mechanisms, bandwidth, efficiency, quality factor, etc., to achieve optimal antenna conditions. For RFID applications, microstrip patch antennas, typically composed by attaching a conductor to a ground plane, are widely preferred. These antennas are predominantly rectangular in shape, although circular shapes for uniform phase excitation of all antenna elements, and meander line shapes for maximizing surface area with a combination of horizontal and vertical lines, have also been reported. Recently, efforts have been ongoing to introduce antenna patterns by printing them directly onto the RFID substrate surface [92–94]. In comparison to traditional methods, antenna printing allows for more sophisticated and complex structures, along with lower manufacturing costs, rapid production, and customization of components [95]. This is expected to significantly contribute to the future design and manufacturing of RFID antennas.

In this way, the RFID sensor tag consists of a substrate that provides the tag's framework, an IC chip that processes information, a sensing area that detects external stimuli, and an antenna that transmits and receives data. With the recent advancements in IoT, the escalating volume of information necessitates the enhancement of RFID performance through the integration of nanomaterials. The development of inkjet printing technology, which can efficiently produce parts with minimal materials under atmospheric pressure or low vacuum compared to existing deposition methods and is compatible with flexible substrates, is also increasing the demand for nanomaterials. Nanomaterials, which have superior surface and interfacial properties compared to bulk materials, can increase the reactivity and achieve excellent sensitivity as sensors by maximizing their surface area. Nanomaterials also have various advantages such as miniaturization, light weight, cost-effectiveness, low power consumption, and efficient integration. Accordingly, many studies have been conducted to implement RFID sensor systems with nanomaterials, which are summarized in Table 1. The introduction of nanomaterials improves the performance of IC chips and antennas, evolving RFID systems into effective communication systems with high throughput and efficient data transmission. Moreover, the use of flexible substrates and various sensing areas configured for wider applications enables the development of next-generation sensor systems that are user-friendly and achieve high sensitivity.

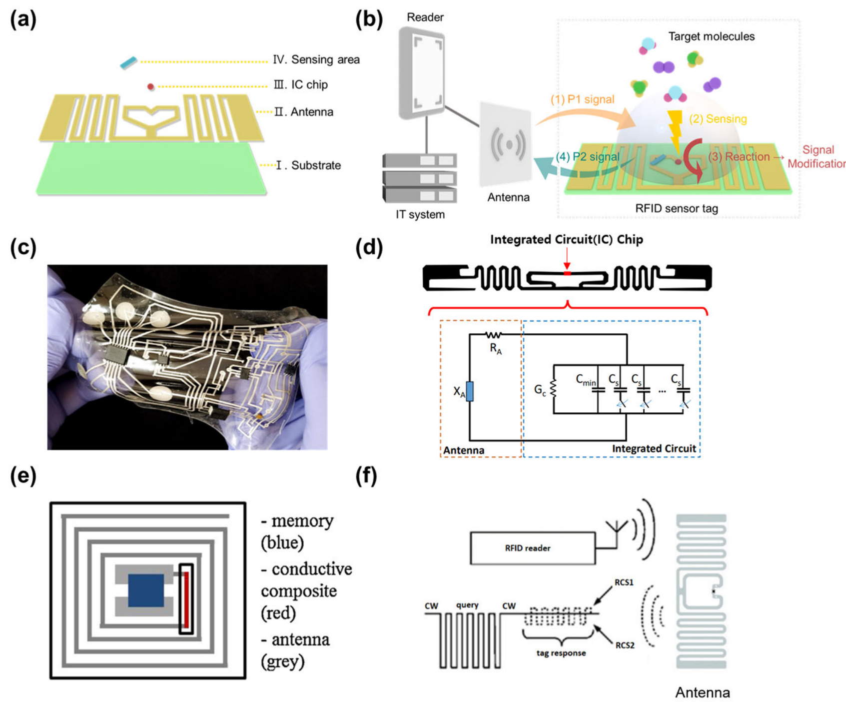

Figure 3. (**a**) The structure of RFID-based wireless sensing tag and (**b**) its operating principles. Each component of the sensing tag: (**c**) the substrate [69], (**d**) the IC chip [71], (**e**) the sensing area [80], and (**f**) the antenna pattern [91].

Table 1. Nanomaterials in RFID sensor system.

Classification	Materials	Component	Property	Analytes	Sensing Range	Sensitivity	LOD	Application	Ref.
Polymer	PET	Substrate	Flexible	-	-	-	-	Gas sensing	[96]
	Nafion 117	Sensing material	Humidity-sensitive	Humidity	3–33%	0.012–0.05%	-	Humidity sensing	[97]
	PDMS	Substrate	Stimuli-responsive	-	-	-	-	-	[98]
	Wheat gluten	Sensing material	CO_2-sensitive	CO_2	0~40%	-	40% CO_2	Food	[99]
	pHEMA	Sensing material	Humidity-sensitive	Humidity	30–80%RH	172% ($\Delta C/C_0$)	-	Agriculture	[100]
Conducting polymer	Carboxyl group-functionalized PPy nanoparticles	Sensing material	NH_3-sensitive	NH_3	0.1–25 ppm	>3%	0.1 ppm	Gas sensing	[64]
	PEDOT:PSS	Sensing material	-	-	-	-	-	Printing technology	[101]
	PANI	Sensing material	NH_3-sensitive	NH_3	0–18 ppm	-	3 ppm	Food	[102]
	PTS-PANI	Sensing material	NH_3-sensitive	NH_3	5–200 ppm	225%(R/R_0)	5 ppm	Food	[103]
Metal nanoparticle	Patterned Ag	Antenna, sensing material	Humidity-sensitive	Humidity	-	-	-	Humidity sensing	[104]
	AgNP/HRP-assisted AuNP	Antenna, sensing material	H_2O_2- and glucose-sensitive	H_2O_2, glucose	10^{-6}—10^{-3} M, 1–20 mM	71%(Δf)	10^{-6} M, 1 mM	Healthcare	[105]
	Dextrin-capped AuNP	Antenna, sensing material	Biosensitive	E. coli	-	-	--	Food	[106]

	Core-shell CuNP	Antenna	High-performance and anti-oxidant	-	-	-	-	Printing technology	[107]
Carbon-based	rGO conductive pattern	Antenna,	Mechanical durability; high electrical conductivity	-	-	-	-	Printing technology	[108]
	SWCNT film (buckypaper)	Antenna, sensing material	Gas-sensitive; isotropic conductivity; good mechanical strength; flexibility	NH_3	-	-	-	Gas sensing	[109]
	MWCNT	Antenna, sensing material	Gas- and temperature-sensitive; lightweight	CO_2, temperature	-	-	-	Temperature sensing, Gas sensing	[110]
	GO film	Antenna	Humidity-sensitive	Humidity	30–99%RH	6.25 MHz/%RH	30%RH	Humidity sensing	[111]
	Graphene	Sensing material	Biochemical-sensitive	Ethanol, KCl, *Staphylococcus aures*	1–5 ppm, 0.008–1 M, 0–1.0 × 10^6 CFU/mL	-	1 ppm, 0.0009 M, 10^5 CFU/mL	Healthcare	[112]
	Graphene oxide	Sensing material	Humidity-sensitive	Humidity	-	-	-	Agriculture	[113]
Composite	Pt-decorated rGO	Sensing material	H_2 gas-sensitive	H_2	1–100 ppm-	-	1 ppm	Gas sensing	[65]
	Ag-rGO	Sensing material	NH_3 gas-sensitive	NH_3	5–100 ppm	1.25%	5 ppm	Gas sensing	[96]
	PANI-incorporated P-GO	Sensing material	NH_3 gas-sensitive	NH_3	2–200 ppm	15.9	1 ppm	Gas sensing	[114]

	rGO/Ag-ink	Antenna, sensing material	NH_3 gas-sensitive	NH_3	0–200 ppm	-	-	Gas sensing	[115]
	ZnO/CuO/rGO	Sensing material	CO_2 gas-sensitive	CO_2	500–1600 ppm	0.009 ppm/dB	500 ppm	Gas sensing	[116]
	Fe_2O_3 hollow nano-particle/PANI:PSS	Sensing material	NO_2 gas-sensitive	NO_2	1–100 ppm	-	0.5 ppm	Gas sensing	[117]
	ZnO/MoS_2/rGO	Antenna, sensing material	Temperature sensitive	Tempera-ture	0–200 °C	1.46 °C/dB	-	Temperature sens-ing	[118]
	Graphite-polyure-thane	Sensing material	pH-sensitive; stretchable	pH	0–14 pH	11.13 ± 5.8 mV/pH	-	Bio sensing	[119]
	Ag ink/CNT	Sensing material	Strain-sensitive	Strain	0–50%	-	-	Healthcare	[120]
	SnO_2/MoS_2/RGO, ZnO/MoS_2/RGO, TiO_2/Co_3O_4/RGO, In_2O_3/CuO/RGO	Sensing material	Humidity-sensitive; tempera-ture-sensitive; light-sensitive; gas-sensitive	Humidity, tempera-ture, light, CO_2	10–50% RH, 5–25 °C, 700–1900 lux, 800–1600 ppm	2 MHz/%RH, 0.63 dB/°C, 0.02 dB/Lux, 0.012 dB/ppm	-	Agriculture	[121]
Others	Aluminum nitride thin film	Sensing material	Temperature-sensitive	Tempera-ture	20–120 °C	64 ppm/°C	-	Temperature sens-ing	[120

Cu-doped ionic liquid	Sensing material	Temperature-sensitive	Temperature	8 °C (threshold)	-	-	Temperature sensing	[122]
Xerogel-based Cu electrode	Antenna	High pattern resolution; mechanical stability	-	-	-	-	Printing technology	[123]
MXene/PdNPs	Antenna, sensing material	Decent printing resolution; conductivity; mechanical robustness; gas-sensitive	Ethylene	0.5–20 ppm	-	0.084 ppm	Gas sensing	[124]
Aerosolized Ag/MWCNT nanocomposite	Antenna	Mechanical durability; strain-sensitive	Strain	0–75°	-	>20%	Strain sensor	[125]
MXene ink	Antenna, sensing material	Large single-layer ratio; narrow flake size distribution; metallic conductivity	Temperature, humidity	20–55 °C, 20–80%RH	-	-	Temperature sensing, humidity sensing	[126]
PAM hydrogel	Sensing material	Wide range of elastic moduli; bio-analytes-sensitive	Pressure, sweat, temperature	0–120 kPa, 0–70 mg/dL, 3–6 pH, 25–45 °C	-	-	Healthcare	[127]
TiO_2	Sensing material	Humidity-sensitive	Humidity	0–100%RH	-	-	Agriculture	[128]

4. Nanomaterials for RFID-Based Sensing System

RFID-based sensing devices achieve wireless detection systems capable of effectively sensing various external stimuli, relying on a variety of nanomaterials. Polymers are predominantly used as substrates due to their cost-effectiveness and ease of processing. Conducting polymers, in particular, garner attention as sensing materials because they can indicate activity for specific substances. Metal nanoparticles and carbon-based materials are used as conductive inks, applied in patterns to RFID components such as antennas and sensing materials. Furthermore, various materials with different compositions and structures are being researched for the advancement of RFID sensors.

4.1. Polymer

Polymers are favored materials for the main substrate of sensor tags. Commonly used polymers include polyethylene terephthalate (PET), polyethylene naphthalate (PEN), polyethersulfone (PES), polyimide (PI), polycarbonate (PC), polydimethylsiloxane (PDMS), and more [129]. For example, Zhang et al. fabricated a RFID sensor based on the cost-effective and mechanically and thermally superior PET substrate [96]. The PET surface was activated by oxygen plasma treatment, and the formed hydroxyl and carboxyl groups facilitated easy drop casting. This resulted in a RFID sensor based on PET that maintained mechanical stability even when bent and preserved integrity in environmental conditions (Figure 4a).

Polymers not only serve as substrates but also provide an environment where other elements such as sensing materials, antennas, and IC chips can operate optimally. For instance, Marchi et al. investigated the impact of the substrate's dielectric constant on the sensitivity of sensing materials for sensor performance optimization (Figure 4b) [97]. A polymer substrate with a high dielectric constant is ineffective in low humidity conditions, which reduce sensor sensitivity. Conversely, in high humidity environments, a polymer substrate with a high dielectric constant proves to be more effective. Table 2 shows the frequency shift and signal amplitude variation values of humidity sensors composed of substrates with different dielectric constants. The dielectric constant of the substrate influences the sensor's sensitivity by varying its mechanism under different conditions. Furthermore, the substrate's dielectric constant affects factors such as impedance matching systems, antenna bandwidth, and overall readout efficiency of a RFID system [130]. Therefore, careful consideration is required in the selection of polymers due to their properties, such as dielectric constant, that influence the sensitivity and communication performance of the RFID sensor.

Table 2. Frequency shifts and signal amplitude variation of humidity sensor based on dielectric substrates [97].

Substrate	Dielectric Constant	RH Low [%]	RH High [%]	Frequency Shift [MHz/%]	$\Delta\|S_{21}\|_{min}$ [dB/%]
DiClad	2.33	15	70	3.909	0.012
RO4003C	3.88	15	75	2.683	0.018
FR4	4.6	10	65	3.454	0.017
RO3010	11.2	10	90	1.562	0.05

When designing tags, the influence of the sensing process on the polymer substrate must be taken into account. For example, Belsey et al. observed the state of PDMS based on exposure to solvent vapors. PDMS serves as the substrate for vapor sensors, and by printing an ink solution of silver, a conductive loop is formed (Figure 4c) [98]. During gas detection, PDMS expands mechanically and forms cracks in the printed silver loop in the presence of solvent vapors. However, upon solvent removal, PDMS contracts, and the silver loop recovers, demonstrating reversible characteristics. Thus, PDMS proves to be a suitable substrate for gas detection environments. Therefore, while numerous polymers exist for sensing-tag substrates, a careful selection of polymers considering their interaction with other elements is essential for withstanding harsh sensing environments.

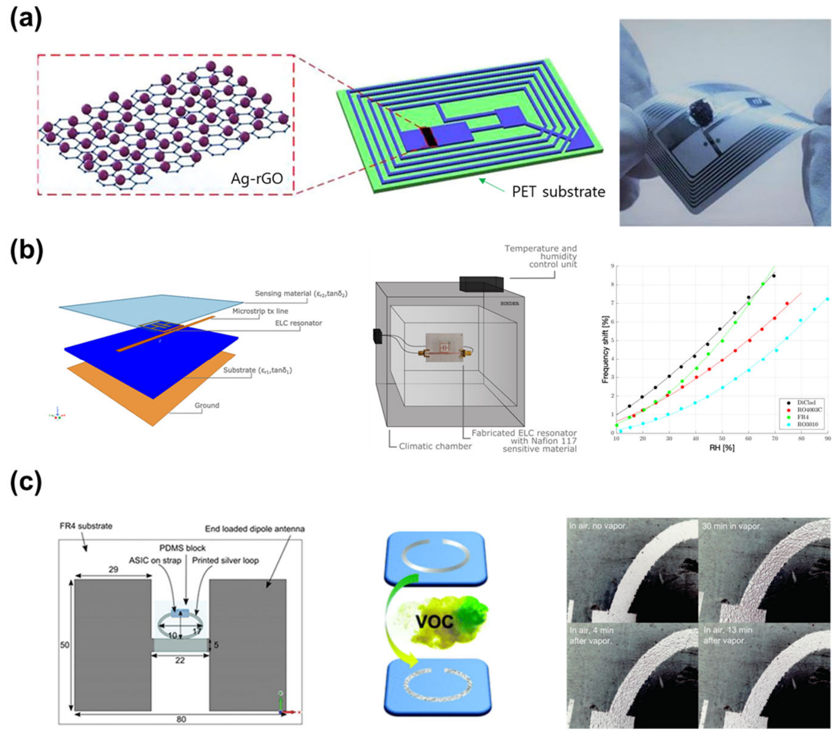

Figure 4. RFID-based sensing-tag substrate formed using various polymers. (**a**) Ammonia gas sensor based on PET substrate [96]. (**b**) Nafion 117 humidity sensor performance depending on the polymer-based substrates of various dielectric constants [97]. (**c**) Swelling and shrinkage of PDMS substrate and preservation of silver ink printed loop structure depending on vapor exposure [98].

Conducting polymers can exhibit various properties due to the conjugation structure of their chains. In particular, the increased density of charge carriers in the polymer chain structure not only enhances electrical conductivity but also allows for high sensitivity to specific compounds by utilizing diverse monomer chemical structures and additional dopants. Commonly used conductive polymers in RFID sensor systems include polyaniline (PANI), polypyrrole (PPy), poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS), polythiophene, and poly(p-phenylene vinylene) [131].

The high electrical conductivity of conductive polymers enables the fabrication of antennas for sensing tags. Guerchouche et al. designed a compact bandwidth antenna for UHF RFID using PEDOT:PSS (Figure 5a) [101]. Despite having lower conductivity than copper, organic polymer-based antennas demonstrated readable distances of up to 75 cm, indicating sufficient performance as antennas. Additionally, these antennas were printed as films on transparent glass substrates, providing optical transparency useful for next-generation displays.

Conducting polymers can selectively respond to specific analytes and are widely used as detection materials due to the ease of adjusting selectivity by controlling various parameters. Nanostructures of conductive polymers, in particular, enhance effective detection of target substances by increasing the interaction sites with the analyte due to a high surface-area-to-volume ratio. For instance, Jun et al. utilized carboxyl-functionalized polypyrrole (C-PPy) nanoparticles as the active material for a sensing tag for detecting ammonia gas (Figure 5b) [64].

While conducting polymers can respond to external environmental stimuli, their resistance changes are relatively small compared to other materials. To overcome this limitation, conducting polymers can form heterojunctions with their opposite semiconductor materials to enhance sensitivity. Tanguy et al. improved the sensitivity of a RFID sensor by introducing n-type phosphonium-functionalized reduced graphene oxide (P-rGO) into p-type semiconductor PANI, forming localized heterojunctions (Figure 5c) [114]. The p-n heterojunction induced a rapid resistance change in the material by altering the depth of the depletion layer, depending on sensing conditions, enhancing the sensor's performance.

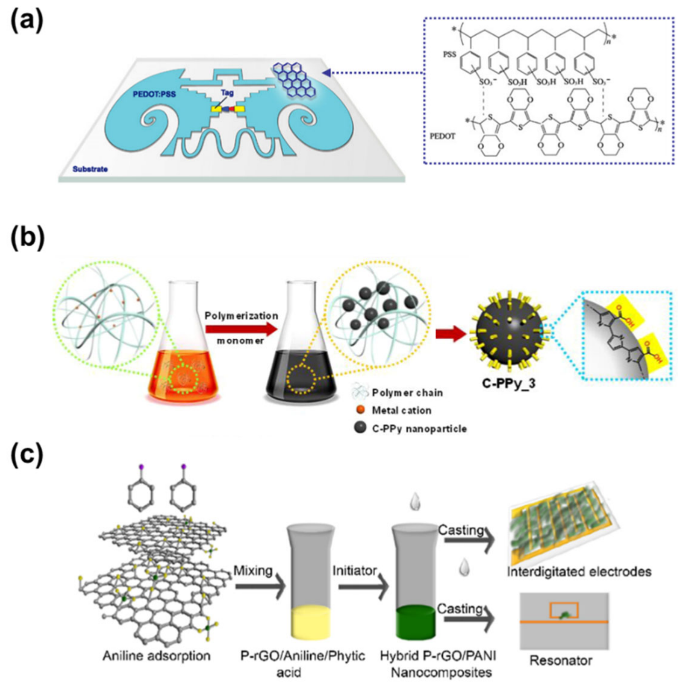

Figure 5. Application of conducting polymers as sensing tag components: (**a**) antenna pattern [101], (**b**) sensing area [64]. (**c**) Application of composite materials formed by bonding conducting polymer with other materials (P-rGO) as sensing area components [114].

4.2. Metal Nanoparticles

Metal nanostructures can be utilized as components of sensing tags due to their large surface area, excellent electrical characteristics, easy processability, and mechanical durability [132]. Metal nanoparticles with high electrical conductivity are desirable materials for conductive inks used in inkjet printing. One significant advantage of metal nanoparticle-based inkjet printing is the ability to easily implement electrical circuits with minimal material usage [133,134]. In the context of RFID sensor systems, it is commonly utilized for the fabrication of patterns or antennas that can replace IC chips. This can reduce the production cost of RFID sensor tags while achieving high throughput. Representative metal nanoparticles used include gold, silver, and copper, and the ink is manufactured by dissolving or suspending these nanoparticles [135]. Particularly, silver nanoparticles, known for their high electrical and thermal conductivity, chemical stability, and low melting point, are widely employed [136]. Luo et al. fabricated a sensing tag without an IC chip by easily replacing it with an antenna through the in-situ metallization of silver nanoparticles (Figure 6a) [104]. This sensing tag demonstrated a capacity of 2 bits without an IC chip, maintaining durability under repetitive tensile and compressive stress while proving excellent adhesion and flexibility.

The conductivity of metal nanoparticle ink directly influences the performance of patterns and antennas in constructing RFID systems. High conductivity indicates active electron mobility within the material, resulting in reduced resistance in electrical circuits and rapid transmission of electrical signals. In other words, improving the conductivity of patterns composed of metal nanoparticles leads to the effective advancement of communication in RFID systems. Various methods have been proposed to enhance the conductivity of metal nanoparticle patterns. One of the representative methods is sintering, which improves conductivity by removing binders and organic stabilizers and forming connections between nanoparticles, and controlling its temperature. For instance, when the sintering temperature of a pattern based on silver nanoparticles was 220 °C, the conductivity was 0.206×10^7 S/m, which was higher than 0.192×10^7 S/m at 170 °C [137]. High sintering temperatures increase the bond strength between particles and grow the crystalline structure, providing an efficient path for electrons to move freely. However, high sintering temperatures damage substrates such as polymers and paper. Therefore, recent efforts focus on maintaining low sintering temperatures while achieving high conductivity. Accordingly, Sahu et al. reported that the limited conductivity of silver nanoparticles can be improved through Cu electroplating [137]. Given the critical role of ink conductivity in effectively advancing RFID systems, numerous studies are required to enhance it.

To overcome the limitations of pure metal nanoparticles, research is underway to enhance properties and characteristics through the combination with other substances. For instance, Larpant et al. designed a biosensor tag capable of wireless monitoring without a battery by controlling the redox conversion of silver nanoparticles (Figure 6b) [105]. The sensing area of the sensing tag was created by pipetting a mixture of silver nanoparticles and horseradish peroxidase (HRP). The interdigitated electrode made from the enzyme–nano material combination achieved high sensitivity through a significant resistance difference of up to 15 times of Ag/AgCl and an accelerated oxidation–reduction process. In another example, Karuppuswami et al. implemented RFID sensing by designing a smart vial for dextrin detection and controlling the surface charge of gold nanoparticles (Figure 6c) [106]. Specifically, in samples with a high concentration of *E. coli*, a decrease in the number of gold nanoparticles attached to the smart vial was observed, resulting in a reduction in resonance frequency shift.

Furthermore, Wang et al. manufactured a stable copper printing paste by controlling the structure of copper nanoparticles (CuNP) through nanostructure control as a replacement for silver paste (Figure 6d) [107]. Surface treatment and heat treatment using formate ligands (FA) were performed to uniformly produce the shell layer of copper particles. The controlled sintering time and temperature in this process improved conductivity. The RFID pattern antenna made from copper paste with added micron-sized copper flakes demonstrated an excellent identification distance of 6.0 cm and superior performance. Additionally, the antenna made through printing showed excellent durability, remaining undamaged against bending and twisting.

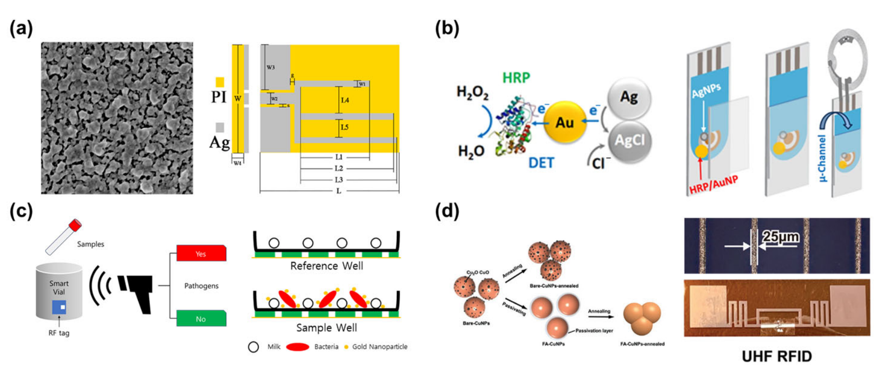

Figure 6. (**a**) Surface shape and antenna structure using Ag/PI film made of in situ metallization and inkjet printing [104]. (**b**) RFID sensor tag based on AuNP ancillary electron transfer between AgNP

and HRP [105]. (**c**) RFID biosensor using d-AuNP and smart vials as markers for *E coli* cells in milk. (**d**) FA-CuNP manufacturing process and application to RFID system [107].

4.3. Carbon Nanostructures

Carbon-based materials are gaining attention as low-density substances with high strength per unit weight, characterized by excellent properties such as high strength, light weight, resistance to corrosion, high heat resistance, and corrosion resistance. These properties make them ideal for the fabrication of components in sensor systems, such as RFID sensor antennas and detection materials [138].

Among them, graphene is widely utilized as a sensing tag component due to its outstanding conductivity, lightweight characteristics, and the potential for flexible component implementation. Song et al. applied reduced graphene oxide (rGO) for the fabrication of patch antenna patterns and sensing detection units (Figure 7a) [115]. As a typical p-type semiconductor, graphene can be utilized as a gas sensing material by inducing electron movement upon contact with oxidizing and reducing gas molecules. Additionally, the high surface area of graphene enhances sensitivity by increasing the surface loading of reactants. Specifically, the researchers applied an ink containing a mixture of rGO and silver nanoparticles to the patch antenna pattern and sensing material. The graphene-based patch antenna achieved a RFID wireless sensing system through changing its radiation characteristics. In this way, the high surface-to-volume ratio and excellent electrical properties of graphene promote its effective utilization as a sensing material.

As mentioned above, metal nanoparticles are mostly used as ink in inkjet printing to form conductive loops. However, its expensive cost and high sintering temperature limit its usage. Consequently, there is a growing interest in graphene inks that are relatively inexpensive and can provide suitable conductivity. Additionally, graphene inks exhibit less aggregation compared to metal nanoparticles, allowing for the formation of uniform printed loops, and their durability is particularly advantageous for implementing flexible components. Notably, Graphene Oxide (GO) and Reduced Graphene Oxide (rGO) are gaining attention as printing inks due to their water dispersibility and self-assembly capabilities. Lv et al. manufactured high-resolution rGO conductive patterns using a responsive inkjet printing technique. The alternate deposition of GO dispersion and reducing agents led to a simple electronic pattern print without requiring additional post-processing (Figure 7b) [108]. The produced rGO patterns exhibited high resolution and conductivity, and they were applied to RFID tags and sensors. The inkjet-printed rGO patterns were well integrated into plasma-treated PET substrates, forming antenna patterns. In this way, graphene-based inkjet printing, which can overcome the limitations of metal nanoparticle-based inks, continues to evolve in the direction of stable ink development and effective process establishment.

Carbon nanotubes (CNTs) are suitable as sensing materials due to their hollow structure, high surface-to-volume ratio, high sensitivity, and rapid response. Additionally, their dispersion in water enables easy integration with flexible substrates through inkjet printing. Occhiuzzi et al. created a UHF RFID sensor tag by forming a CNT film that could alter its electrical conductivity in response to analytes (Figure 7c) [109]. The produced CNT film, integrated into the tag antenna in a rectangular shape, affected the radiation performance of the antenna. By modifying the resistance load and adjusting the impedance of the tag, detection was achieved in the UHF band of RFID. Habib et al. implemented a chipless RFID sensor tag using an MWCNT-based sensing material through complete inkjet printing (Figure 7d) [110]. The MWCNT solution mixed with water was injected into the meandered structured detection slot of the tag at room temperature, forming the sensing area. MWCNTs responded sensitively to the concentration of analytes, altering their resistance, which, in turn, affected the electromagnetic energy returning to the reader. This passive RFID tag demonstrated the ability to transmit 5 bits of data and effectively function as a sensor without electronic components. Although its performance, such as electrical conductivity, stable ink formation, and relatively low sensitivity, still needs to be improved, carbon materials are expected to enable the low-cost and easy implementation of next-generation RFID sensor tags with flexibility and excellent durability.

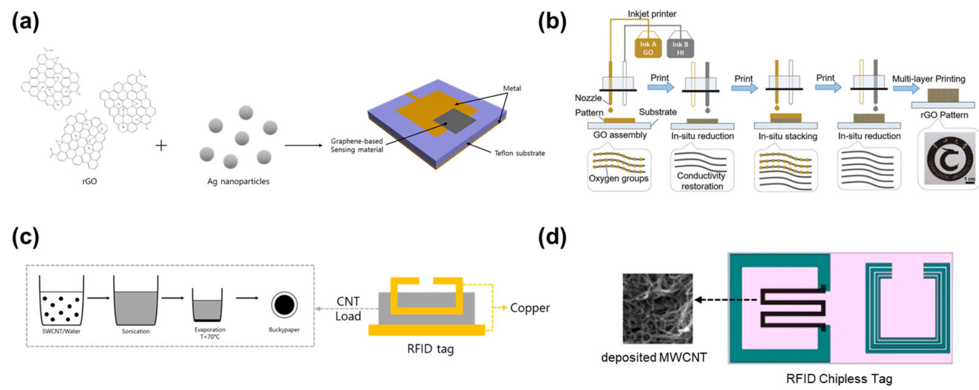

Figure 7. (**a**) rGO-based ammonia-sensitive hybrid materials and their antenna applications. (**b**) In situ patterning and reduction process of rGO patterns called reactive inkjet printing [108]. (**c**) Passive RFID sensor tag based on CNT film integrated in antenna. (**d**) Chipless RFID sensor manufactured with full inkjet printing using MWCNT solution [110].

4.4. Others

To enhance RFID performance, the utilization of new forms and composite materials beyond conventional ones is required. Among the improved RFID technologies, Surface Acoustic Wave (SAW) RFID operating in the GHz range is considered one that can operate over long distances and penetrate obstacles like metal and liquids.

Aluminum nitrate (AlN) possesses characteristics such as high acoustic velocity, low dielectric and propagation loss, and good chemical resistance, making it a widely researched material in SAW applications. Lamanna et al. have fabricated a disposable SAW RFID sensor capable of high-frequency operation based on AlN and a flexible substrate (Figure 8a) [139]. The AlN pattern deposited on a PEN film allows Lamb SAW to propagate with a rapid wave phase velocity of 10,600 m/s.

There is another type of sensor based on acoustic waves, utilizing Bulk Acoustic Wave (BAW). Unlike SAW, which propagates along the surface of the material, BAW propagates through the bulk of the medium [140]. BAW-based RFID sensors which operate in higher frequency ranges provide a wider reading range compared to SAW-based sensors. Additionally, they are less sensitive to external environmental factors such as temperature and bending deformation and can achieve relatively high sensitivity [141]. However, due to the complex manufacturing processes and costs, BAW sensors are still in the early stages of development, requiring further research.

Research is also underway for RFID sensors utilizing ionic liquids (IL) that exist in a liquid state even below a certain temperature. Vivaldi et al. have developed a temperature-detecting RFID sensor tag for cold chain monitoring using copper ionic liquid (Cu-IL) (Figure 8b) [122]. Cu-IL integrates into the RFID sensor by being placed in small drops between two electrodes. When the temperature exceeds the melting point of Cu-IL (8 °C), it melts, achieving detection by transitioning the electrodes from an open to a closed state.

The sintering process of metal nanoparticles requires high temperatures, causing deformation in typical plastic substrates. To address this issue, researchers are exploring the enhancement of the adhesive, thermal, and structural properties of metal nanoparticles through the assistance of other substances. Wang et al. have produced a copper electrode usable as an antenna for RFID tags by employing soft and mesoporous Xerogel (Figure 8c) [123]. After creating the Xerogel framework by printing copolymer-based ink, they loaded a catalyst through ion exchange, providing active sites for copper particle growth. The resulting Xerogel-based Cu electrode antenna demonstrated stable signal transmission and reception even under bending conditions.

MXene's high conductivity, hydrophilicity, and dispersibility make it suitable as ink in the field of printed electronics. Li et al. have created an ethylene-modulated resonator for RFID-based sensors by integrating palladium nanoparticles (PdNP) into additive-free MXene ink (Figure 8d) [124]. The approach of growing PdNP in MXene ink has led to the flexibility of devices, enabling effective detection and in situ sensing. The RF resonator based on MXene-reduced Pd NP ink exhibited low LOD (0.084 ppm), appropriate selectivity at room temperature, and effective wireless sensing performance.

Min et al. proposed a straightforward process by aerodynamically focused printing Ag/MWCNT composites, maintaining electrical properties without the need for post-processing (Figure 8e) [125]. Aerosolization, achieved by using compressed air's excitation and purging, allows the rapid deposition of nanomaterials without chemical bonding or heat treatment, enabling direct and simple printing. The printed composite nanomaterial demonstrated transparency, flexibility, and effective functionality as a RFID-based sensor.

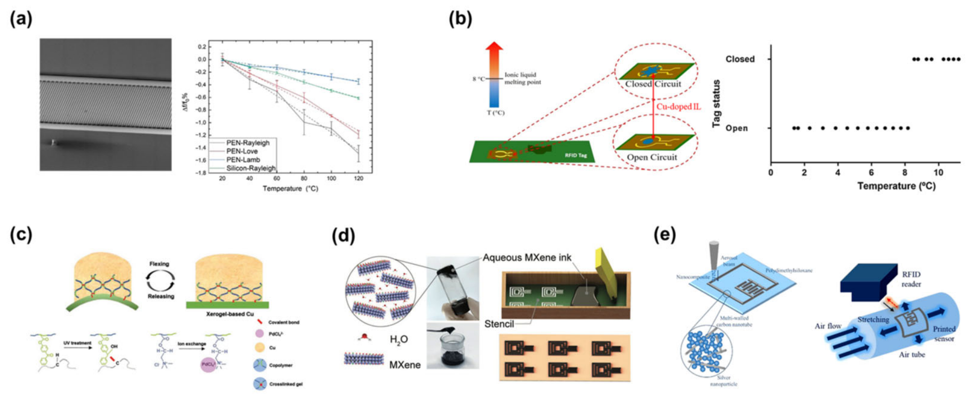

Figure 8. (**a**) Digital-to-digital transducers manufactured by AlN sputtering and their standardized resonant frequency shift [139]. (**b**) Manual RFID tag using Cu-doped IL as a sensitive material [122]. (**c**) Solution-processable copper electrodes made by inkjet printing of a Xerogel scaffold [132]. (**d**) Water-based MXene-based ink for screen printing [124]. (**e**) The manufacturing process of printing aerosolized nanocomposites consisting of Ag and MWCNT and its multi-strain sensor application method [125].

5. Applications

RFID-based sensing systems formed using various materials can be used in various fields as follows in real life.

5.1. Gas Sensing

Invisible harmful gases, which affect not only human respiratory systems but also the overall metabolism, need to be detected swiftly, even in trace amounts. RFID sensor systems enabling low-cost wireless detection of hazardous substances utilize various nanomaterials to effectively detect gas molecules [142]. Lee et al. implemented a wireless hydrogen gas detection system by introducing Pt-decorated reduced graphene oxide (Pt-rGO) nanocomposites into the antenna of a UHF-RFID tag (Figure 9a) [65]. When the sensor is exposed to gas, Pt particles adsorb hydrogen gas molecules, causing electrons to move to rGO, leading to a change in material resistance. The change in antenna resistance causes impedance mismatch, allowing the RFID system to identify the detection. Pt_rGO firmly fixed on a flexible plastic substrate exhibits significant mechanical durability and demonstrates high detection capabilities for hydrogen gas without an external power source.

Miao et al. used a nanocomposite composed of three components, ZnO, CuO and rGO, to effectively detect carbon dioxide (Figure 9b) [116]. The formation of rod-shaped ZnO and petal-shaped CuO composites increases adsorption sites for gas molecules, and the introduction of rGO with excellent electrical conductivity enhances the sensitivity of the detection material. The three-layered structured composite material shows a sensitivity of 0.009 ppm/dB, a response time of 29.1 s, and exhibits repeatability and stability, effectively detecting carbon dioxide at room temperature.

Kim et al. created a detection pattern for nitrogen dioxide using multi-dimensional and porous Fe_2O_3 nanoparticles produced through dual nozzle electrospinning (Figure 9c) [117]. A composite paste, produced by introducing PANI:PSS as a conductive matrix, is incorporated into the antenna pattern, demonstrating detection performance over a wide range of NO_2 gas concentrations from 0.5 ppm to 50 ppm. The selection of various nanomaterials, structural control, and composite formation enhance the sensitivity of the RFID system's detection material, enabling effective detection.

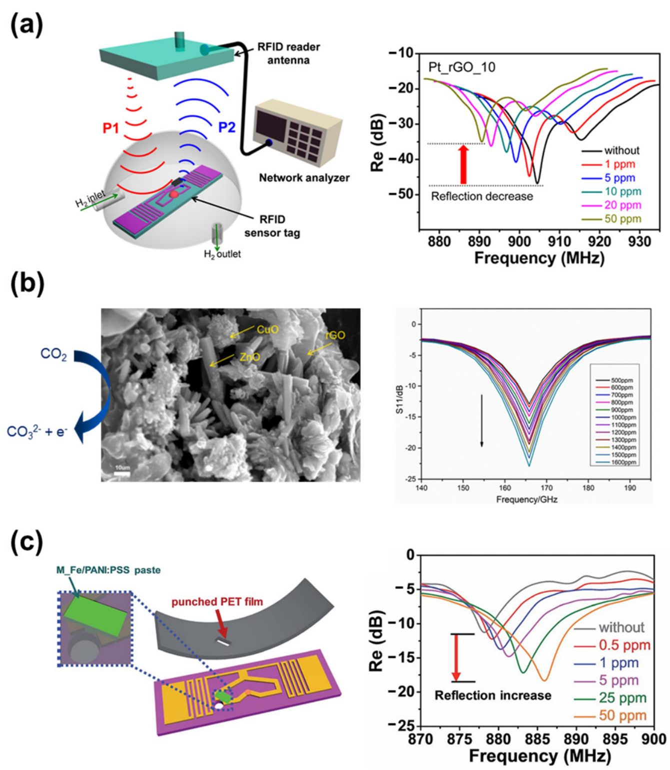

Figure 9. (**a**) A hydrogen smart sensor system based on Pt/graphene fixed RFID tag [65]. (**b**) Passive chipless CO_2 sensor using ZnO/CuO/rGO nanocomposites at room temperature [116]. (**c**) Organic conductive nanocomposite paste-based high-sensitivity wireless NO_2 gas sensor composed of multi-dimensional Fe_2O_3 hollow nanoparticles [117].

5.2. Environmental Monitoring

Monitoring the quality of air, water, and other environmental factors is crucial to protect human health and life from external harmful elements [143]. RFID systems are widely utilized in applications related to this field because they can wirelessly and in real time collect and report continuous information about the environment.

High humidity can generate harmful substances like mold, leading to the corrosion of structures and adversely affecting human health [144]. Additionally, rapid temperature changes can cause expansion or contraction of structures, resulting in damage and causing conditions such as dehydration or hypothermia that hinder normal human body function [145]. From an inventory management perspective, uncontrolled temperatures can degrade the quality of goods transported and stored in large quantities [146]. RFID tags can analyze abnormal behavior in temperature and humidity by collecting real-time information from a distance.

Xue et al. proposed a chipless RFID humidity sensor based on paper with high sensitivity and quality factors (Figure 10a) [111]. To optimize resonance characteristics, a toroidal-shaped inductor-interdigitated electrode capacitor and double copper-coated paper with a significantly shifted resonance frequency were employed in the fabrication of the RFID humidity sensor. The moisture-sensitive GO-coated electrode achieved a detection range of 60%RH to 90%RH and an improved sensitivity of 6.25 MHz/%RH. This is attributed to the synergy between the moisture absorption capacity of the paper substrate itself and water molecule adsorption in GO.

Miao et al. fabricated an ultra-high speed and high-sensitivity RFID temperature sensor using ZnO/MoS_2/RGO nanocomposite material (Figure 10b) [118]. Introducing MoS_2 with a large surface area and rGO with high electrical conductivity to ZnO, a well-known temperature-sensitive material, resulted in a nanocomposite with excellent temperature detection characteristics. The temperature-sensitive microstrip antenna, fabricated using thermal transfer technology, demonstrated outstanding temperature detection performance with a linear relationship in the range of 0 to 200 °C, a recovery time of less than 10 s, and temperature hysteresis of less than 0.34 °C.

Shao et al. produced a functional flexible electronic device capable of detecting both temperature and humidity by printing it with additive-free MXene aqueous ink at room temperature (Figure 10c) [126]. The fabricated RFID sensor undergoes changes in electrical conductivity as the PDMS substrate expands with increasing temperature, stretching the MXene conductive network. Moreover, exposure of MXene to humidity causes swelling in the interlayer structure of the nanosheets, altering electrical conductivity and enabling humidity detection. The flexible sensor, printed using printing technology, effectively detects temperature and humidity when attached to plants or the human body.

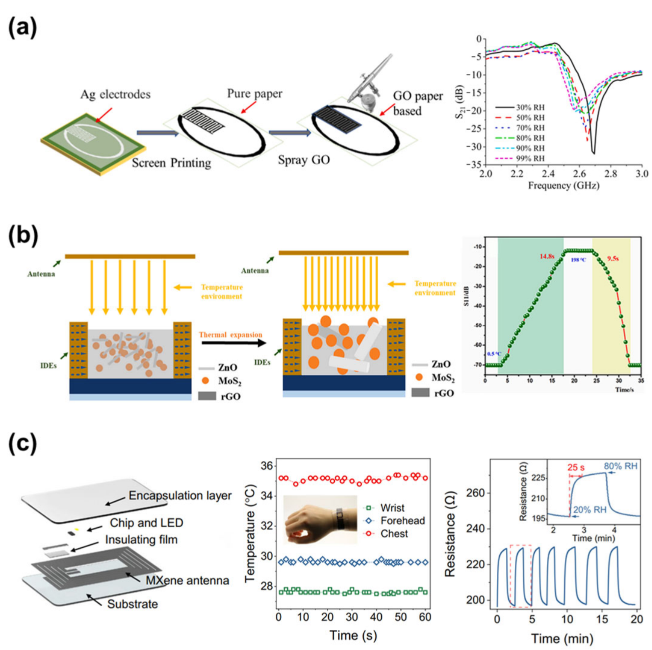

Figure 10. (**a**) High-sensitivity paper-based chipless RFID sensor for humidity monitoring [111]. (**b**) Manual RFID sensor tag with ZnO/MoS_2/RGO modified microstrip antenna for temperature monitoring [118]. (**c**) Mxene ink-based flexible wireless electronics that enable improved printing for temperature and humidity detection [126].

5.3. Healthcare

Measuring physiological signals and automatically diagnosing them, mobile healthcare that provides medical services freely without being constrained by time, space, or location is currently attracting significant attention. Wireless sensors collect the patient's bio and environmental information, allowing real-time and organic feedback to the overall healthcare system [147].

Xu et al. proposed a wireless sensor tag capable of analyzing gases, ions, bacteria, and more [112]. As shown in Figure 11a, when the concentration of the analyzed substance exceeds the threshold marked by the red line, the smartphone recognizes it and can read the corresponding value. By varying the resistance of the rheostat within a single tag, various threshold values can be set without the need for multiple tags. Graphene-coated carbonic interdigitated electrodes grown by chemical vapor deposition (CVD) were used for ethanol detection. The graphene exposed to the target gas undergoes a change in impedance by physically adsorbing gas molecules. Potassium chloride ions and *Staphylococcus aureus* bacteria were detected through gold and platinum electrodes, respectively. The sensor demonstrated low limits of detection (LOD) of 1 ppm for ethanol, 0.009 M for KCl, and 105 CFU/mL for bacteria, showing excellent linearity and sensitivity, effectively detecting various biochemical substances.

Glucose monitoring is recognized as a powerful tool for early diagnosis of diabetes. Gao et al. proposed a biosensor for non-contact detection of glucose concentration based on a RFID system [148]. The sensor tag is fabricated by integrating a capacitor produced by Cu plating and a PDMS microchannel providing excellent biological characteristics and compatibility onto a glass substrate. The tag exhibits variations in permittivity based on the presence and concentration of glucose, altering the effective capacitance of the Cu-based squared spiral capacitor. Glucose, with its relatively higher molecular weight compared to water molecules, induces a viscous effect that interferes with the rotation of the AC field, resulting in changes in permittivity. Based on this mechanism, the reader induces reflection parameters, generating deviations in resonance frequency, thereby achieving glucose detection. The glucose sensor demonstrates larger shifts in resonance frequency with increasing glucose concentrations within the range of 25 mg/dL to 600 mg/dL, proving excellent linearity. The RFID-based bio-sensor tag, composed of a PDMS channel and a copper-based spiral capacitor, has successfully achieved non-contact glucose detection. Ongoing research is actively exploring further advancements in glucose detection.

Dang et al. developed a wearable sweat pH monitoring sensor that can maintain contact even with human movements (Figure 11b) [119]. Since sweat contains valuable information such as glucose, lactate, and cortisol, reflecting the intensity of physical activity and dehydration levels, its analysis is highly beneficial for health assessment. The researchers manufactured pH-sensitive electrodes at low temperatures, selecting a graphite–polyurethane composite for flexibility and rapid responsiveness to analyze sweat. This led to effective pH monitoring with a high sensitivity of 11.13 ± 5.8 mV/pH on a wearable substrate.

Dutta et al. implemented a sensor with LEDs attached to the resonator of an NFC sensor circuit, enabling intuitive understanding of the user's state (Figure 11c) [127]. They structured hydrogel as an interlayer, advancing RF resonators to wearable applications without rigid materials. This device effectively reported the body's response to pressure, sweat, and temperature changes as a soft sensor skin.

Niu et al.'s sensor system, bodyNET, comprehensively monitors human physiological signals through networking, utilizing RFID technology in the healthcare field (Figure 11d) [120]. They used a flexible polymer substrate made of poly(styrene-b-ethylene-butadiene) (SEBS), inductor patterns, and a flexible capacitor bottom electrode with silver conductive ink and CNT as the strain-detecting substance. By attaching the sensor to various positions on the body, they could analyze pulse, respiration, and body movement simultaneously and continuously. The bodyNET system, capable of securely adhering to the body and interpreting multiple signals comprehensively, is expected to contribute effectively to the next generation of personal health monitoring. The flexibility of components friendly to the human body and the analysis capability for various substances make RFID sensor systems even more promising in the healthcare field.

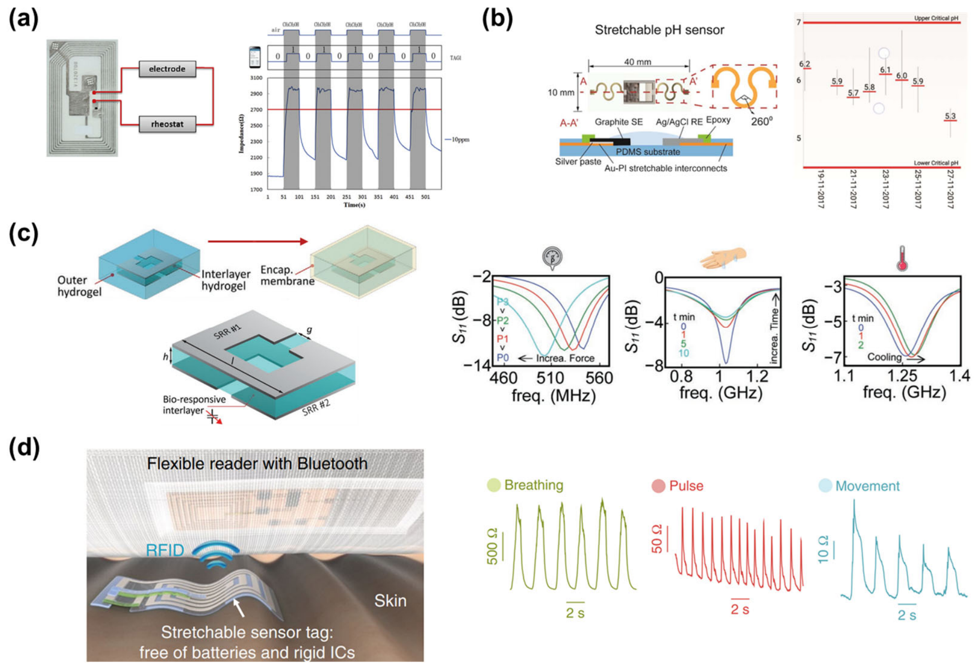

Figure 11. (**a**) NFC-based wireless biosensor using rheostat [110]. (**b**) Graphite–polyurethane composite-based stretchable wireless system for sweat pH monitoring [119]. (**c**) Multifunctional hydrogel-interlayer RF/NFC resonator and its in vivo implementation performance [127]. (**d**) BodyNET stretchable sensor system that simultaneously monitors human body movement, pulse and breathing [120].

5.4. Food Fresh Management

RFID, which has strengths in inventory management, allows for convenient and effective monitoring of food quality [149]. Detecting food spoilage is crucial due to its potential consequences for human health and environmental issues. Monitoring of food involves the analysis of gases or bacteria occurring within the packaging [150].

Bibi et al. conducted research on food quality through carbon dioxide monitoring using the intriguing properties of wheat gluten, a polar substance, at high relative humidity (Figure 12a) [99]. Wheat gluten, when in contact with carbon dioxide at 90% relative humidity, serves as a detecting material by changing its electrical and dielectric characteristics, effectively integrated into a UHF RFID system operating at 868 MHz.

Karuppuswami et al. proposed a biosensor using Dextrin-capped gold nanoparticles (d-AuNP) as markers for quality management of milk (Figure 12b) [106]. The resonant frequency shifts in capacitive loading, depending on the bacteria count in contaminated milk, were measured to analyze the concentration of *E. coli* C3000. Detection through the attachment of conductive nanoparticles and cells enabled the development of a RFID sensor, demonstrating a low threshold of 5 log CFU/mL bacteria.

Ammonia is a harmful gas generated by bacteria during the protein-containing food spoilage process. Karuppuswami et al. applied highly conductive polymer PANI with an affinity for ammonia to a wireless sensor system (Figure 12c) [102]. The system, combining PANI thin films with high ammonia affinity with a RFID system, enabled wireless and long-distance monitoring of food quality, exhibiting the capability to detect small amounts of ammonia (3 ppm) at room temperature and atmospheric pressure. Ma et al. enhanced detection performance by adding p-toluene sulfonate hexahydrate (PTS) to PANI (PTS-PANi). As shown in Figure 12d, PTS-PANI formed a porous structure with a larger surface area and smaller diameter, demonstrating sensitivity to analytes [103]. This detection material successfully achieved detection not only for ammonia but also for actual biological amines such as putrescine and cadaverine, showing $\Delta R/R_0$ values of 46% and 17%, respectively.

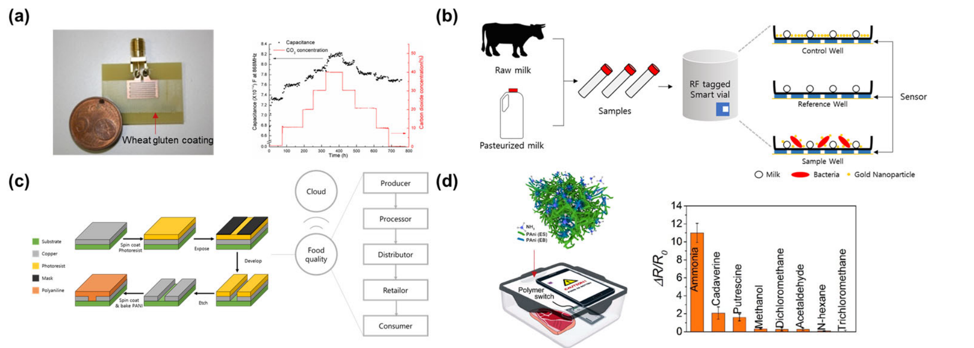

Figure 12. (**a**) Digital-to-digital capacitor system cast from wheat gluten and its CO_2 monitoring performance [99]. (**b**) Schematic diagram of liquid food supply chain monitoring sensor using gold nanoparticle marker and frequency shift according to d-AuNP concentration. (**c**) RFID-combined manual digital sensors for packaged foods and direct probing for ammonia detection. (**d**) Nanostructure conductive polymer-based food spoilage sensors and their ammonia, cadaverine, and putrescine selectivity [103].

5.5. Agriculture

As the scale of farms expands, the need for effective management and supervision in agriculture has become increasingly essential. RFID sensor tags can detect various environmental parameters such as temperature, humidity, and light. Through their large-scale information processing capabilities, they enhance the efficiency of crop and environmental management.

Cappelli et al. developed a passive RFID sensor tag for soil moisture monitoring (Figure 13a) [128]. They first formed a thin-film circuit on a silicon substrate through lithography, sputtering, and lift-off processes to establish the foundation for measuring soil impedance and fringe capacitance. Subsequently, they coated the sensor with TiO_2 nanoparticles for humidity measurement. The functionalization using TiO_2 nanoparticles achieved significant sensitivity, especially at humidity levels exceeding 50%RH. This sensor operates independently of soil composition and effectively measures various soil moisture levels without the need for frequent calibration.

Reddy et al. designed a humidity sensor using Ag nanoparticles and poly (2-hydroxyethyl methacrylate) (pHEMA) (Figure 13b) [100]. The sensor, printed on a flexible PET substrate, introduced Ag nanoparticles as interdigitated capacitors. Following this, they deposited humidity-sensitive pHEMA on the interdigitated capacitors with a fixed thickness. This sensor exhibited excellent linearity in humidity measurements, ranging from 30%RH to 80%RH, with a maximum error range of 0.6 to 0.8%, demonstrating its stability. This sensor is expected to be actively used in the smart agriculture field.

Miao et al. implemented a multifunctional sensor capable of detecting humidity, temperature, light, and CO_2 gas (HTLC) by combining various nanomaterials (Figure 13c) [121]. Composites composed of pure SnO_2, MoS_2, ZnO, TiO_2, Co_3O_4, $In2O_3$, CuO, and RGO solutions were manufactured using a thermal method. By combining these materials, the researchers created sensors with specific characteristics, such as SnO_2/MoS_2/RGO for humidity detection, ZnO/MoS_2/RGO for temperature sensitivity, TiO_2/Co_3O_4/RGO for light intensity sensitivity, and In_2O_3/CuO/RGO for CO_2 gas sensitivity. Each environmental parameter was measured at separate frequencies or amplitudes, ensuring no interference. The HTLC multidimensional sensor based on RFID systems is expected to effectively monitor complex agricultural environments.

Li et al. utilized graphene-based films to construct an effective system for agriculture information monitoring (Figure 13d) [113]. They proposed a system capable of real-time collection and transmission of diverse and large amounts of data through wireless networks of various sensors. Among the numerous sensors, those utilizing graphene active films demonstrated non-destructive and accurate monitoring of leaf moisture. The high surface area of graphene effectively increased the monitoring sensitivity of the sensor. Consequently, the real-time and mass information processing capabilities of RFID systems contribute to the systematic management of the agricultural field, where monitoring of various environmental variables is crucial.

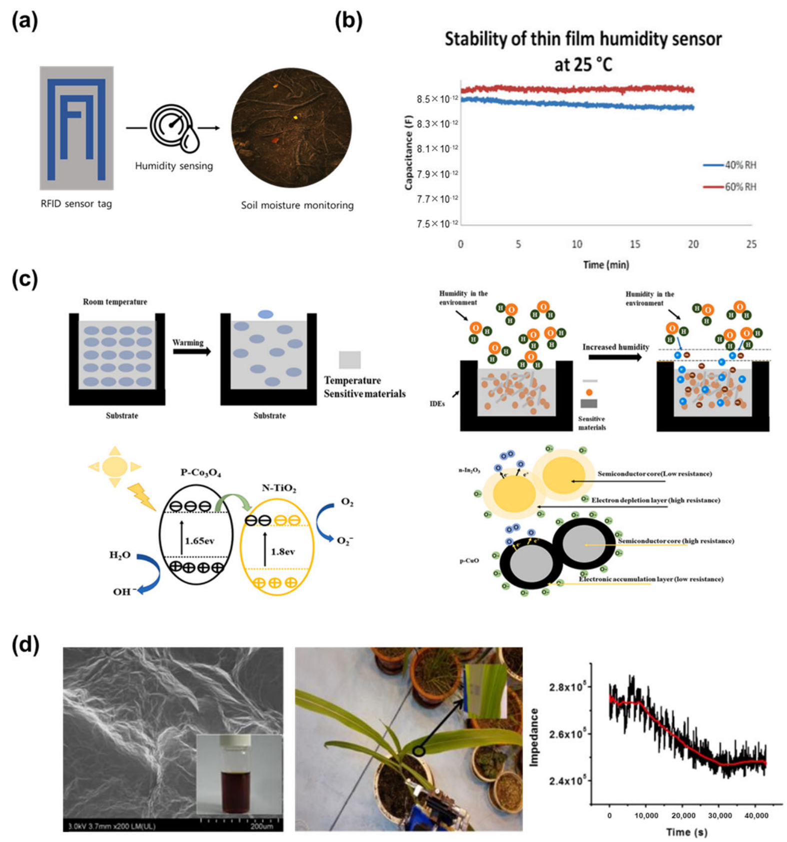

Figure 13. (**a**) Passive HF RFID tag sensor for soil moisture measurement. (**b**) Humidity detection capability of a fully printed RFID sensor utilizing pHEMA [100]. (**c**) Operation of a passive RFID multidimensional integrated sensor for humidity, temperature, light, and CO_2 detection [121]. (**d**) Leaf moisture monitoring using graphene active film [113].

5.6. Others

In addition, RFID sensor systems are widely utilized in various fields such as stock management, railway, shipping, electronic toll systems, automotive, and aerospace. With the expanding applications of RFID technology, there is an increasing demand for efficient measurement of physical and chemical parameters, as well as diverse information collection and processing in different environments. Consequently, there is a growing movement to enhance the performance of RFID components using nanomaterials. As an example, Machiels et al. suggested an efficient inventory management through the implementation of smart packaging using a paper substrate and highly compatible silver ink [151]. They facilitated the potential of smart boxes capable of effectively managing large inventories by connecting high-frequency RFID chips to the screen-printed conductive adhesive on paper. Mejias-Morillo et al. attempted to improve the performance of passive wireless sensors used in the space industry through Kapton wrapping of the antenna conductive surface [152]. As a result, the sensor achieved a detection range of up to 3.2 m and a mean measurement error of less than 1%. These efforts would lead to broader applications of RFID technology. Additionally, with the increasing demand for user-friendly electronic devices, research is actively progressing to advance RFID sensor components, ensuring their superior performance and stable operation even in wearable environments. Tekcin et al. reported on the impact of the sintering process on RF antenna performance after printing conductive ink using the pad printing method [153]. The sintered printed sensor enabled wireless data transmission at shorter range and demonstrated stable operation in wearable and moisture-sensitive environments. In this way, research is actively underway to implement diverse nanomaterials and manufacturing methods for RFID systems to be applied in various fields.

6. Summary and Perspectives

The RFID sensor system is a type of wireless communication technology that detects specific stimuli from the external environment remotely and responds to them. By selecting appropriate materials for each component and processing them in various ways, improved communication functionality and detection performance can be achieved (Figure 14). Polymers can successfully implement flexible and elastic substrates, and nanomaterials such as conductive polymers, metal nanoparticles, and carbon-based substances can be produced with conductive inks for effective integration into the system through printing. These materials can be used as functional patterns that replace various components of RFID systems, including sensing materials, antennas, and IC chips. The introduction of each component through printing is expected to make future RFID sensor manufacturing more convenient and efficient.

The necessity for research on nanomaterials to advance RFID as an efficient communication system and sensor continues to grow. In the case of the substrate, which is the basis for other components, it is required to design it considering the effects of polymer properties, such as dielectric constant and mechanical properties, on other components. With the expansion of the wearable market, achieving not only excellent flexibility but also transparency is expected to broaden the applications of RFID sensor systems. In addition, it is necessary to improve the properties and performance of metal nanoparticles, which provide excellent electrical properties, while developing carbon-based materials to replace them at a relatively low price. As there is an increasing demand to produce RFID components using relatively simple and cost-effective inkjet printing, research on improving the viscosity, conductivity, resolution, and performance of the inks is essential.

The introduction of nanomaterials has transformed RFID into a more effective sensor system. Currently, RFID sensor tags are being applied across various fields, effectively monitoring gas, temperature, humidity, human sensing, food quality, and agriculture. Ongoing research will guide RFID towards achieving enhanced performance, including a broader operating range, superior data transmission capabilities, and excellent sensitivity to external environments, enabling its diverse applications. In the future, the RFID system is anticipated to be more widely utilized as a smart and user-friendly next-generation sensor in the Internet of Things (IoT) environment.

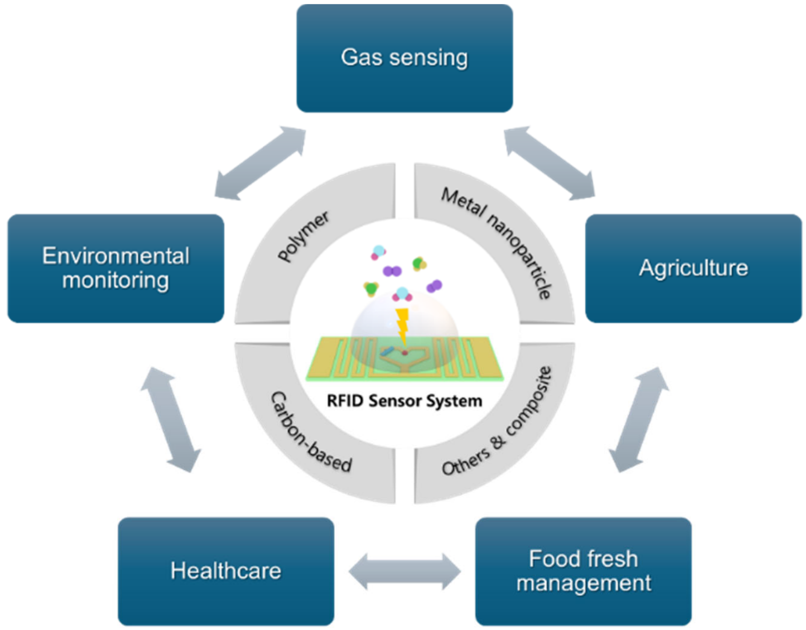

Figure 14. Future work of RFID sensor systems used in various fields with the introduction of nanomaterials.

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References

1. Nadeem, I.; Alibakhshikenari, M.; Babaeian, F.; Althuwayb, A.A.; Virdee, B.S.; Azpilicueta, L.; Khan, S.; Huynen, I.; Falcone, F.; Denidni, T.A. A comprehensive survey on 'circular polarized antennas' for existing and emerging wireless communication technologies. *J. Phys. D Appl. Phys.* **2022**, *55*, 033002.
2. Khanh, Q.V.; Hoai, N.V.; Manh, L.D.; Le, A.N.; Jeon, G. Wireless communication technologies for IoT in 5G: Vision, applications, and challenges. *Wirel. Commun. Mob. Comput.* **2022**, *2022*, 3229294.
3. Niyato, D.; Kim, D.I.; Maso, M.; Han, Z. Wireless powered communication networks: Research directions and technological approaches. *IEEE Wirel. Commun.* **2017**, *24*, 88–97.
4. Feng, X.; Yan, F.; Liu, X. Study of wireless communication technologies on internet of things for precision agriculture. *Wirel. Pers. Commun.* **2019**, *108*, 1785–1802.
5. Pattanik, S.K.; Samal, S.R.; Bandopadhaya, S.; Swain, K.; Choudhury, S.; Das, J.K.; Mihovska, A.; Poulkov, V. Future wireless communication technology towards 6G IoT: An application-based analysis of IoT in real-time location monitoring of employees inside underground mines by using BLE. *Sensors* **2022**, *22*, 3438.
6. Landaluce, H.; Arjona, L.; Perallos, A.; Falcone, F.; Angulo, I.; Muralter, F. A review of IoT sensing applications and challenges using RFID and wireless sensor networks. *Sensors* **2020**, *20*, 2495.
7. Xu, G.; Shen, W.; Wang, X. Applications of wireless sensor networks in marine environment monitoring: A survey. *Sensors* **2014**, *14*, 16932–16954.

8. Buratti, C.; Conti, A.; Dardari, D.; Verdone, R. An overview on wireless sensor networks technology and evolution. *Sensors* **2009**, *9*, 6869–6896.
9. Corke, P.; Wark, T.; Jurdak, R.; Hu, W.; Valencia, P.; Darren, M. Environmental wireless sensor networks. *Proc. IEEE* **2010**, *98*, 1903–1917.
10. Veeramani, S.; Mahammad, S.N. An approach to place sink node in a wireless sensor network(WSN). *Wirel. Pers. Commun.* **2019**, *111*, 1117–1127.
11. Mainetti, L.; Palano, L.; Patraono, M.; Stefanizzi, M.L.; Vergallo, R. Integration of RFID and WSN technologies in a Smart Parking System. In Proceedings of the 2014 22nd International Conference on Software, Telecommunications and Computer Networks (SoftCOM), Split, Croatia, 17–19 September 2014; pp. 104–110.
12. Zhong, R.Y.; Dai, Q.Y.; Qu, T.; Hu, G.J.; Huang, G.Q. RFID-enabled real-time manufacturing execution system for mass-customization production. *Robot. Comput. Integr. Manuf.* **2013**, *29*, 283–292.
13. Irani, Z.; Gunasekaran, A.; Dwivedi, Y.K. Radio frequency identification (RFID): Research trends and framework. *Int. J. Prod. Res.* **2010**, *48*, 2485–2511.
14. Cui, L.; Zhang, Z.; Gao, N.; Meng, Z.; Li, Z. Radio frequency identification and sensing techniques and their applications—A review of the state-of-the-art. *Sensors* **2019**, *19*, 4012.
15. Xiao, Y.; Yu, S.; Wu, K.; Ni, Q.; Janecek, C.; Nordstad, J. Radio frequency identification: Technologies, applications, and research issues. *Wirel. Commun. Mob. Comput.* **2007**, *7*, 457–472.
16. Valero, E.; Adán, A.; Cerrada, C. Evolution of RFID applications in construction: A literature review. *Sensors* **2015**, *15*, 15988–16008.
17. Chen, J.C.; Chen, C.; Huang, P.B. Supply chain management with lean production and RFID application: A case study. *Expert Syst. Appl.* **2013**, *40*, 3389–3397.
18. Domdouzis, K.; Kumar, B.; Anumba, C. Radio-Frequency Identification (RFID) applications: A brief introduction. *Adv. Eng. Inform.* **2007**, *21*, 350–355.
19. Chen, J.C.; Cheng, C.H.; Huang, P.B.; Wang, K.J.; Huang, C.J.; Ting, T.C. Warehouse management with lean and RFID application: A case study. *J. Adv. Manuf. Technol.* **2013**, *69*, 531–542.
20. Ruiz-Garcia, L.; Lunadei, L. The role of RFID in agriculture: Applications, limitations and challenges. *Comput. Electron. Agric.* **2011**, *79*, 42–50.
21. Xie, L.; Yin, Y.; Vasilakos, A.V.; Lu, S. Managing RFID data: Challenges, opportunities and solutions. *IEEE Commun. Surv. Tutor.* **2014**, *16*, 1294–1311.
22. Samadi, S. Applications and opportunities for radio frequency identification (RFID) technology in intelligent transportation systems: A case study. *Int. J. Inf. Eng. Electron. Bus.* **2013**, *3*, 341–345.
23. Kawakita, Y.; Nakamura, O.; Uo, Y.; Murai, J. Use of RFID at large-scale events. *IATSS Res.* **2005**, *29*, 31–39.
24. Zhang, J.; Sunny, A.L.; Zhang, G.; Tian, G. Feature extraction for robust crack monitoring using passive wireless RFID antenna sensors. *IEEE Sens. J.* **2018**, *18*, 6273–6280.
25. Luo, Y.; Pu, L.; Wang, G.; Zhan, Y. RF Energy Harvesting Wireless Communications: RF Environment, Device Hardware and Practical Issues. *Sensors* **2019**, *19*, 3010.
26. Varma, D.S.; Ram, G.; Kumar, G.A. Time-modulated multi-tone antenna array for wireless information and power transfer. *Int. J. Commun.* **2022**, *36*, e5419.
27. Yao, S.; Ren, P.; Song, R.; Liu, Y.; Huang, Q.; Dong, J.; O'Connor, B.T.; Zhu, Y. Nanomaterial-enabled flexible and stretchable sensing systems: Processing, integration, and applications. *Adv. Mater.* **2020**, *32*, 1902343.
28. Li, W.; Zhan, X.; Song, X.; Si, S.; Chen, R.; Liu, J.; Wang, Z.; He, J.; Xiao, X. A review of recent applications of ion beam techniques on nanomaterial surface modification: Design of nanostructures and energy harvesting. *Small* **2019**, *31*, 1901820.
29. Moinudeen, G.K.; Ahmad, F.; Kumar, D.; Al-Douri, Y.; Ahamd, S. IoT applications in future foreseen guided by engineered nanomaterials and printed intelligence technologies a technology review. *IEEE Internet Things J.* **2017**, *6*, 106–148.
30. Choy, K.L.; Ho, G.T.S.; Lee, C.K.H. A RFID-based storage assignment system for enhancing the efficiency of order picking. *J. Intell. Manuf.* **2014**, *28*, 111–129.
31. Subramanian, V.; Frechet, J.M.M.; Chang, P.C.; Huang, D.C.; Lee, J.B.; Molesa, S.E.; Redinger, D.R.; Volkman, S.K. Progress toward development of all-printed RFID tags: Materials, processes, and devices. *Proc. IEEE* **2005**, *93*, 1330–1338.
32. Saarinen, K.; Björninen, T.; Ukkonen, L.; Frisk, L. Reliability analysis of RFID tags in changing humid environment. *IEEE Trans. Compon. Packag. Manuf. Technol.* **2014**, *4*, 77–85.
33. Potyrailo, R.A.; Nagraj, N.; Tang, Z.; Mondello, F.J.; Surman, C.; Morris, W. Battery-free radio frequency identification (RFID) sensors for food quality and safety. *J. Agric. Food Chem.* **2012**, *60*, 8535–8543.
34. Potyrailo, R.A.; Morris, W.G.; Sivavec, T.; Tomlinson, H.W.; Klensmeden, S.; Lindh, K. RFID sensors based on ubiquitous passive 13.56-MHz RFID tags and complex impedance detection. *Wirel. Commun. Mob. Comput.* **2008**, *9*, 1318–1330.
35. Gee, K.M.; Andandarajah, P.; Colline, D. Current progress towards the integration of thermocouple and chipless RFID technologies and the sensing of a dynamic stimulus. *Micromachines* **2020**, *11*, 1019.
36. Baumbauer, C.L.; Anderson, M.G.; Ting, J.; Sreekumar, A.; Rabaey, J.M.; Arias, A.C.; Thielens, A. Printed, flexible, compact UHF-RFID sensor tags enabled by hybrid electronics. *Sci. Rep.* **2020**, *10*, 16543.
37. Yang, W.; Cheng, X.; Guo, Z.; Sun, Q.; Wang, J.; Wang, C. Design, fabrication and applications of flexible RFID antennas based on printed electronic materials and technologies. *J. Mater. Chem. C* **2023**, *11*, 406–425.

38. Sun, X.; Zhan, C.; Li, H.; Yu, H.; Zhang, J.; Qiu, H.; Liang, J.; Wu, J.; Su, M.; Shi, Y.; et al. Wearable near-field communication sensors for healthcare: Materials, fabrication and application. *Micromachines* **2022**, *13*, 784.
39. Sanchez-Romaguera, V.; Wünscher, S.; Turki, B.M.; Abbel, R.; Barbosa, S.; Tate, D.J.; Oyeka, D.; Batchelor, J.C.; Parker, E.A.; Schubert, U.S.; et al. Inkjet printed paper based frequency selective surfaces and skin mounted RFID tags: The interrelation between silver nanoparticle ink, paper substrate and low temperature sintering technique. *J. Mater. Chem. C* **2015**, *3*, 2132–2140.
40. Sarycheva, A.; Polemi, A.; Liu, Y.; Dandekar, K.; Anasori, B.; Gogotsi, Y. 2D titanium carbide (MXene) for wireless communication. *Sci. Adv.* **2018**, *4*, eaau0920.
41. Nath, B.; Reynolds, F.; Want, R. RFID technology and applications. *IEEE Pervasive Comput.* **2006**, *5*, 22–24.
42. Rzalli, M.S.; Mahdi, M.A.; Ismail, A.; Shafie, S.M.; Adam, H. Design and development of wireless communication transceiver to support RFID reader at UHF band. *J. Electromagn. Waves Appl.* **2010**, *24*, 14–15.
43. Baballe, M.A.; Nababa, F.A. A Comparative Study on Radio Frequency Identification System and Its Various Applications. *Int. J. Adv. Appl. Sci.* **2021**, *10*, 392–398.
44. Kabachinski, J. An Introduction to RFID. *Biomed. Instrum. Technol.* **2005**, *39*, 131–134.
45. Herrojo, C.; Paredes, F.; Mata-Contreras, J.; Martin, F. Chipless-RFID: A review and recent developments. *Sensors* **2019**, *19*, 3385.
46. Preradovic, S.; Chander, N.; Balbin, I. RFID transponders. *IEEE Microw. Mag.* **2008**, *9*, 90–103.
47. White, G.R.T.; Gardiner, G.; Prabhakar, G.P.; Razak, A.A. A comparison of barcoding and RFID technologies in practice. *J. Inf. Technol.* **2007**, *2*, 119–132.
48. Alamin, M.; Tian, G.Y.; Andrews, A.; Jackson, P. Corrosion detection using low-frequency RFID technology. *Insight* **2012**, *54*, 72–75.
49. Cai, A.; Qing, X.M.; Chen, Z.N. High frequency RFID smart table antenna. *Microw. Opt. Technol. Lett.* **2007**, *49*, 2074–2076.
50. Aslam, B.; Kashif, M.; Amin, Y.; Tenhunen, H. Low-profile magnetically coupled dual resonance patch antenna for UHF RFID applications. *Int. J. Electron. Commun.* **2021**, *133*, 153672.
51. Jiang, B.; Smith, J.R.; Philipose, M.; Roy, S.; Sundara-Rajan, K.; Mamishev, A.V. Energy Scavenging for Inductively Coupled Passive RFID Systems. *IEEE Trans. Instrum. Meas.* **2007**, *56*, 118–125.
52. Tran, A.; Bolic, M.; Yagoub, M. Magnetic-field coupling characteristics of ferrite-coil antennas for low-frequency RFID applications. *Int. J. Comput. Sci. Eng.* **2010**, *7*, 7–11.
53. Mishra, P.; Bolic, M.; Yagoub, M.; Stewart, R. RFID technology for tracking and tracing explosives and detonators in mining services applications. *J. Appl. Geophys.* **2012**, *76*, 33–43.
54. Meng, Z.; Li, Z. RFID tag as a sensor-a review on the innovative designs and applications. *Meas. Sci. Rev.* **2016**, *6*, 305–315.
55. Gu, Y.; Roh, S.; Lin, W.; Jung, Y.; Cho, Y. Investigation of the signal reach performance of the ultra-high-frequency identification tag for underground utility management. *Appl. Sci.* **2023**, *13*, 2294.
56. Zhu, J.; Chen, G.; Tian, G.; Liu, H. Underground passive LF RFID localization method based on magnetic field model of reader coil antenna. *IEEE Trans. Instrum. Meas.* **2023**, *73*, 8000410.
57. Ching, S.; Tai, A. HF RFID versus UHF RFID-technology for library service transformation at city university of hong kong. *J. Acad. Librariansh.* **2009**, *35*, 347–359.
58. Barge, P.; Merlino, G.; Tortia, C. Radio frequency identification technologies for livestock management and meat supply chain traceability. *Can. J. Anim. Sci.* **2013**, *93*, 23–33.
59. Abad, E.; Palacio, F.; Nuin, M.; Zarate, G.; Juarros, A.; Gomez, J.; Marco, S. RFID smart tag for traceability and cold chain monitoring of foods: Demonstration in an intercontinental fresh fish logistic chain. *J. Food Eng.* **2009**, *93*, 394–399.
60. Kaur, M.; Sandhu, M.; Mohan, N.; Sandhu, P.S. RFID technology principles, advantages, limitations & its applications. *Int. J. Electr. Comput. Eng.* **2011**, *3*, 1793–8163.
61. Xiao, G.; Aflaki, P.; Lang, S.; Zhang, Z.; Tao, T.; Py, C.; Lu, P.; Martin, C. Printed UHF RFID reader antennas for potential retail applications. *IEEE J. Radio Freq. Identif.* **2018**, *2*, 31–37.
62. Montanaro, T.; Sergi, I.; Motroni, A.; Buffi, A.; Nepa, P.; Pirozzi, M.; Catarinucci, L.; Colella, R.; Chietera, F.P.; Patrono, L. An IoT-aware smart system exploiting the electromagnetic behavior of UHF-RFID tags to improve worker safety in outdoor environments. *Electronics* **2022**, *11*, 717.
63. Zhang, X.; Tentzeris, M. Applications of fast-moving RFID tags in high-speed railway systems. *Int. J. Eng. Bus. Manag.* **2011**, *3*, 27–31.
64. Jun, J.; Oh, J.; Shin, D.H.; Kim, S.G.; Lee, J.S.; Kim, W.; Jang, J. Wireless, room temperature volatile organic compound sensor based on Polypyrrole nanoparticle immobilized ultrahigh frequency radio frequency identification tag. *ACS Appl. Mater. Interfaces* **2016**, *8*, 33139–33147.
65. Lee, J.S.; Oh, J.; Jun, J.; Jang, J. Wireless hydrogen smart sensor based on Pt/Graphene-immobilized radio-frequency identification tag. *ACS Nano* **2015**, *9*, 7783–7790.
66. Babar, A.A.; Bjornien, T.; Bhagavati, V.A.; Sydanheimo, L.; Kalio, P.; Ukkonen, L. Small and flexible metal mountable passive UHF RFID tag on high-dielectric polymer-ceramic composite substrate. *IEEE Antennas Wirel. Propag. Lett.* **2012**, *11*, 1319–1322.
67. Kuo, S.K.; Hsu, J.; Hung, Y. Analysis and design of an UHF RFID metal tag using magnetic composite material as substrate. *Prog. Electromagn. Res. B* **2010**, *24*, 49–62.
68. Björninen, T.; Babar, A.A.; Elsherbeni, A.; Ukkonen, L. Compact metal mountable UHF RFID tag on a barium titanate based substrate. *Prog. Electromagn. Res. C* **2012**, *26*, 43–57.

69. Lopes, P.A.; Fernandes, D.F.; Silva, A.F.; Marque, D.G.; de Almeida, A.T.; Majidi, C.; Tavakoli, M. Bi-phasic Ag–In–Ga-embedded elastomer inks for digitally printed, ultra-stretchable, multi-layer electronics. *ACS Appl. Mater. Interfaces* **2021**, *13*, 14552–14561.
70. Tedjini, S.; Kakrmakar, N.; Perret, E.; Vena, A.; Koswatta, R.; E-Azim, R. Hold the Chips: Chipless Technology, an Alternative Technique for RFID. *IEEE Microw. Mag.* **2013**, *14*, 56–65.
71. Costa, F.; Genovesi, S.; Borgese, M.; Michel, A.; Dicandia, F.A.; Manara, G. A review of RFID sensors, the new frontier of internet of things. *Sensors* **2021**, *21*, 3138.
72. Mulloni, V.; Donelli, M. Chipless RFID sensors for the internet of things: Challenges and opportunities. *Sensors* **2020**, *20*, 2135.
73. Vena, A.; Perret, E.; Tedjini, S. Chipless RFID tag using hybrid coding Technique. *IEEE Trans. Microw. Theory Tech.* **2011**, *59*, 3356–3364.
74. Subrahmannian, A.; Behera, S.K. Chipless RFID: A unique technology for mankind. *IEEE J. Radio Freq. Identif.* **2022**, *6*, 151–163.
75. Weng, Y.F.; Cheung, S.W.; Yuk, T.I.; Liu, L. Design of chipless UWB RFID system using a CPW multi-resonator. *IEEE Antennas Propag. Mag.* **2013**, *55*, 13–31.
76. Garbati, M.; Perret, E.; Siragusa, R.; Halopè, C. Toward chipless RFID reading systems independent of tag orientation. *IEEE Microw. Wirel. Compon. Lett.* **2017**, *27*, 1158–1160.
77. Genovesi, S.; Costa, F.; Monorchio, A.; Manara, G. Chipless RFID tag exploiting multifrequency delta-phase quantization encoding. *IEEE Antennas Wirel. Propag.* **2016**, *15*, 738–741.
78. Dey, S.; Saha, J.K.; Karmakar, N.C. Smart Sensing: Chipless RFID Solutions for the Internet of Everything. *IEEE Microw. Mag.* **2015**, *16*, 26–39.
79. Babaeian, F.; Karmakar, N.C. Development of Cross-Polar Orientation-Insensitive Chipless RFID Tags. *IEEE Trans. Antennas Propag.* **2020**, *68*, 5159–5170.
80. Fiddes, K.L.; Yan, N. RFID tags for wireless electrochemical detection of volatile chemicals. *Sens. Actuators B* **2013**, *186*, 817–823.
81. Pang, F.; Li, S.; Sun, W.; Han, G. Reversible conductivity modulation of PEDOT:PSS based on pH. *Mater. Chem. Phys.* **2017**, *186*, 246–250.
82. Spielberg, D.H.; Arndt, R.A.; Damask, A.C.; Lefkowitz, I. Dielectric and neutron inelastic scattering measurements on phenanthrene. *J. Chem. Phys.* **1971**, *54*, 2597–2601.
83. Mittal, M.; Kumar, A. Carbon nanotube (CNT) gas sensors for emissions from fossil fuel burning. *Sens. Actuators B Chem.* **2014**, *203*, 349–362.
84. Deng, F.; Zuo, P.; Wen, K.; Wu, X. Novel soil environment monitoring system based on RFID sensor and LoRa. *Comput. Electron. Agric.* **2020**, *169*, 105169.
85. Yao, W.; Chu, C.; Li, Z. The adoption and implementation of RFID technologies in healthcare: A literature review. *J. Med. Syst.* **2011**, *36*, 3507–3525.
86. Kumar, P.; Reinitz, H.W.; Simunovic, J.; Sandeep, K.P.; Franzon, P.D. Overview of RFID technology and its applications in the food industry. *J. Food Sci.* **2009**, *74*, R101–R106.
87. Asad, M.; Sheikhi, M.H. Highly sensitive wireless H_2S gas sensors at room temperature based on CuO-SWCNT hybrid nanomaterials. *Sens. Actuators B* **2016**, *231*, 474–483.
88. Clément, P.; Ramos, A.; Lazaro, A.; Molina-luna, L.; Bittencourt, C.; Gribau, D.; Llobet, E. Oxygen plasma treated carbon nanotubes for the wireless monitoring of nitrogen dioxide levels. *Sens. Actuators B* **2015**, *208*, 444–449.
89. Potyrailo, R.A.; Surman, C.; Morris, W.G.; Go, S.; Lee, Y.; Cella, J.; Chichak, K.S. Selective quantitation of vapors and their mixtures using individual passive multivariable RFID sensors. In Proceedings of the 2010 IEEE International Conference on RFID (IEEE RFID 2010), Orlando, FL, USA, 14–16 April 2010; pp. 22–28.
90. Le, N.N.; Fribourg-blanc, E.; Phan, H.C.T.; Dang, D.M.T.; Dang, C.M. A RFID-based wireless NH3 gas detector using spin coated carbon nanotubes as sensitive layer. *Int. J. Nanotechnol.* **2018**, *15*, 3–13.
91. Zhao, A.; Sunny, A.I.; Li, L.; Wang, T. Machine learning-based structural health monitoring using RFID for harsh environmental conditions. *Electronics* **2022**, *11*, 1740.
92. Zaid, J.; Abdulhadi, A.E.; Denidni, T.A. Miniaturized multi-port microstrip patch antenna using metamaterial for passive UHF RFID-tag sensor applications. *Sensors* **2019**, *19*, 1982.
93. Wan, G.; Kang, W.; Wang, C.; Li, W.; Li, M.; Xie, L.; Chen, L. Separating strain sensor based on dual-resonant circular patch antenna with chipless RFID tag. *Smart Mater. Struct.* **2021**, *30*, 015007.
94. Sarsri, N.; Myllymäki, S.; Sonkki, M.; Srifi, M.N. Matching approach for UHF RFID tag antenna immersed in dielectric materials. *Comput. Electr. Eng.* **2020**, *84*, 106611.
95. Shin, K.Y.; Hong, J.Y.; Jang, J. Micropatterning of graphene sheets by inkjet printing and its wideband dipole-antenna application. *Adv. Mater.* **2011**, *23*, 2113–2118.
96. Zhang, L.; Tan, Q.; Kou, H.; Wu, D.; Zhang, W.; Xiong, J. Highly sensitive NH_3 wireless sensor based on Ag-RGO composite operated at room-temperature. *Sci. Rep.* **2019**, *9*, 9942.
97. Marchi, G.; Mulloni, V.; Acerbi, F.; Donelli, M.; Lorenzelli, L. Tailoring the performance of a Nafion 117 humidity chipless RFID sensor: The choice of the substrate. *Sensors* **2023**, *23*, 1430.
98. Belsey, K.E.; Parry, A.V.S.; Rumen, C.V.; Ziai, M.A.; Yeates, S.G.; Batchelor, J.C.; Holder, S.J. Switchable disposable passive RFID vapour sensors from inkjet printed electronic components integrated with PDMS as a stimulus responsive material. *J. Mater. Chem. C* **2017**, *5*, 3167.

99. Bibi, F.; Guilaume, C.; Gontard, N.; Soril, B. Wheat gluten, a bio-polymer to monitor carbon dioxide in food packaging: Electric and dielectric characterization. *Sens. Actuators B Chem.* **2017**, *250*, 76–84.
100. Reddy, A.S.G.; Narakathu, B.B.; Atashbar, M.Z.; Rebros, M.; Rerosova, E.; Joyce, M.K. Fully printed flexible humidity sensor. *Procedia Eng.* **2011**, *25*, 120–123.
101. Guerchouche, K.; Herth, E.; Calvet, L.E.; Roland, N.; Loyez, C. Conductive polymer based antenna for wireless green sensors applications. *Microelectron. Eng.* **2017**, *182*, 46–52.
102. Karuppuswami, S.; Mondal, S.; Kumar, D.; Chahal, P. RFID coupled passive digital ammonia sensor for quality control of packaged food. *IEEE Sens. Lett.* **2020**, *20*, 4679.
103. Ma, Z.; Chen, P.; Cheng, W.; Yan, K.; Pan, L.; Shi, Y.; Yu, G. Highly sensitive, printable nanostructured conductive polymer wireless sensor for food spoilage detection. *Nano Lett.* **2018**, *18*, 4570–4575.
104. Luo, M.; Liu, Z.; Li, Z.; Wang, Q.; Liu, R.; Xu, Y.; Wang, K.; Shi, X.; Ye, S. Patterned Ag/PI RFID tag integrated with humidity sensing by in situ metallization. *Langmuir* **2022**, *38*, 11478–11485.
105. Larpant, N.; Pham, A.D.; Shafaat, A.; Gonzalez-martinez, J.F.; Sotres, J.; Sjöholm, J.; Laiwattanapaisal, W.; Faridbod, F.; Genjali, M.R.; Arnebard, T.; et al. Sensing by wireless reading Ag/AgCl redox conversion on RFID tag: Universal, battery-less biosensor design. *Sci. Rep.* **2019**, *9*, 12948.
106. Karuppuswami, S.; Matta, L.L.; Alocilja, E.C.; Chahal, P. A wireless RFID compatible sensor tag using gold nanoparticle markers for Pathogen detection in the liquid food supply chain. *IEEE Sens. Lett.* **2018**, *2*, 350704.
107. Wang, L.; Xia, F.; Xu, W.; Wang, G.; Hong, S.; Cheng, F.; Wu, B.; Zheng, N. Antioxidant high-conductivity copper pastes based on core–shell copper nanoparticles for flexible printed electronics. *Adv. Funct. Mater.* **2023**, *33*, 2215127.
108. Lv, S.; Ye, S.; Chen, C.; Zhang, Y.; Wu, Y.; Wang, Y.; Tang, R.; Souxa, M.M.D.; Liu, X.; Zhao, X. Reactive inkjet printing of graphene based flexible circuits and radio frequency antennas. *J. Mater. Chem. C* **2021**, *9*, 13182–13192.
109. Occhiuzzi, C.; Rida, A.; Marrocco, G.; Tentzeris, M. RFID passive gas sensor integrating carbon nanotubes. *IEEE Trans. Microw. Theory* **2011**, *59*, 2674.
110. Habib, A.; Akram, S.; Ali, M.R.; Muhammad, T.; Zainab, S.; Jehangir, S. Radio frequency identification temperature/CO_2 sensor using carbon nanotubes. *Nanomaterials* **2023**, *13*, 273.
111. Xue, Y.; Hou, B.; Wang, S.; Shang, Y.; Chen, B.; Ju, Y. A highly sensitive paper-based chipless RFID humidity sensor based on graphene oxide. *Sens. Actuators A Phys.* **2023**, *358*, 114457.
112. Xu, G.; Zhang, Q.; Lu, Y.; Liu, L.; Ji, D.; Li, S.; Liu, Q. Passive and wireless near field communication tag sensors for biochemical sensing with smartphone. *Sens. Actuators B Chem.* **2017**, *246*, 748–755.
113. Li, G.; Li, D.; Che, W.; Zhang, Y.; Xu, S. Design and application of special sensors and internet of things (IoT)-based wireless system for agricultural information monitor. *J. Phys. Conf. Ser.* **2020**, *1646*, 012130.
114. Tanguy, N.R.; Wiltshire, B.; Arjmand, M.; Zarifi, M.H.; Yan, N. Highly sensitive and contactless ammonia detection based on nanocomposites of phosphate-functionalized reduced graphene oxide/polyaniline immobilized on microstrip resonators. *ACS Appl. Mater. Interfaces* **2020**, *12*, 9746–9754.
115. Song, L.; Wu, B.; Zhang, X.; Huang, B. Demonstration of wireless gas sensor using reduced graphene oxide loaded patch antenna. In Proceedings of the 2018 IEEE International Conference on Computational Electromagnetics (ICCEM), Chengdu, China, 26–28 March 2018; pp. 1–3.
116. Miao, F.; Wu, H.; Tao, B.; Zang, Y. A passive-chipless LC carbon dioxide sensor with non-contact ZnO/CuO/RGO nanocomposites at room temperature. *Vacuum* **2023**, *215*, 112261.
117. Kim, S.G.; Jun, J.; Lee, J.S.; Jang, J. A highly sensitive wireless nitrogen dioxide gas sensor based on an organic conductive nanocomposite paste. *J. Mater. Chem. A* **2019**, *7*, 8451.
118. Miao, F.; Tian, P.; Tao, B.; Zang, Y. Passive RFID microstrip antenna sensor for temperature monitoring. *Vacuum* **2022**, *201*, 111108.
119. Dang, W.; Manjakkal, L.; Navaraj, W.T.; Lorenzelli, L.; Vinciguerra, V.; Dahiya, R. Stretchable wireless system for sweat pH monitoring. *Biosens. Bioelectron.* **2018**, *107*, 192–202.
120. Niu, S.; Matsuhisa, N.; Beker, L.; Li, J.; Wang, J.; Jiang, Y.; Yan, X.; Yun, Y.; Bernett, W.; Poon, A.S.Y.; et al. A wireless body area sensor network based on stretchable passive tags. *Nat. Electron.* **2019**, *2*, 361–368.
121. Miao, F.; Han, Y.; Tian, P.; Tao, B.; Zang, Y.; Chu, P.K. Integrated sensor for humidity, temperature, light, and carbon dioxide based on passive RFID. *Sens. Actuators B Chem.* **2023**, *390*, 133913.
122. Vivaldi, F.; Melai, B.; Bonini, A.; Poma, N.; Salvo, P.; Kirchhain, A.; Tintori, S.; Bigongiari, A.; Bertuccelli, F.; Isola, G.; et al. A temperature-sensitive RFID tag for the identification of cold chain failures. *Sens. Actuators A Phys.* **2020**, *313*, 112182.
123. Wang, S.; Gao, Y.; Huang, Q.; Guo, X.; Yang, A.; Zhang, Y.; Zhuang, Q.; Chen, D.; Chen, L.; Ju, X.; et al. Inkjet-printed xerogel scaffolds enabled room-temperature fabrication of high-quality metal electrodes for flexible electronics. *Adv. Funct. Mater.* **2022**, *32*, 2203730.
124. Li, X.; Sun, R.; Pan, J.; Shi, Z.; Lv, J.; An, Z.; He, Y.; Chen, Q.; Han, R.P.S.; Zhang, F.; et al. All-MXene-printed RF resonators as wireless plant wearable sensors for in situ ethylene detection. *Small* **2023**, *19*, 2207889.
125. Min, S.; Kim, H.; Quan, Y.; Kim, H.; Lyu, J.; Lee, G.; Ahn, S. Stretchable chipless RFID multi-strain sensors using direct printing of aerosolised nanocomposite. *Sens. Actuators A Phys.* **2020**, *313*, 112224.
126. Shao, Y.; Wei, L.; Uw, X.; Jaing, C.; Yao, Y.; Peng, B.; Chen, H.; Huangfu, J.; Ying, Y.; Zhang, C.J.; et al. Room-temperature high-precision printing of flexible wireless electronics based on MXene inks. *Nat. Commun.* **2022**, *13*, 3223.

127. Dautta, M.; Alshetaiwi, M.; Escobar, A.; Torres, F.; Bernardo, N.; Tseng, P. Multi-functional hydrogel-interlayer RF/NFC resonators as a versatile platform for passive and wireless biosensing. *Adv. Electron. Mater.* **2020**, *6*, 1901311.
128. Cappelli, I.; Fort, A.; Mugnaini, M.; Panzardi, E.; Pozzebon, A.; Tani, M.; Vignoli, V. Battery-less LF RFID sensor tag for soil moisture measurements. *IEEE Trans. Instrum. Meas.* **2020**, *70*, 9504113.
129. Yakimets, I.; MacKerron, D.; Giesen, P.; Kilmartin, K.J.; Goorhuis, M.; Meinders, E.; MacDonald, W.A. Polymer substrates for flexible electronics: Achievements and challenges. *Adv. Mater. Res.* **2010**, *93–94*, 5–8.
130. Zaid, J.; Farahani, M.; Denidni, T.A. Magneto-dielectric substrate-based microstrip antenna for RFID applications. *IET Microw. Antennas Propag.* **2017**, *11*, 1389–1392.
131. Yoon, H.; Jang, J. Conducting-polymer nanomaterials for high-performance sensor applications: Issues and challenges. *Adv. Funct. Mater.* **2009**, *19*, 1567–1576.
132. Murray, R.W. Nanoelectrochemistry: Metal nanoparticles, nanoelectrodes, and nanopores. *Chem. Rev.* **2008**, *108*, 2688–2720.
133. Szczech, J.B.; Megaridis, C.M.; Zhang, J.; Gamota, D.R. Ink jet processing of metallic nanoparticle suspensions for electronic circuitry fabrication. *Nanoscale Microscale Thermophys. Eng.* **2004**, *8*, 327–339.
134. Nayak, L.; Mohanty, S.; Nayak, S.K.; Ramadoss, A. A review on inkjet printing of nanoparticle inks for flexible electronics. *J. Mater. Chem. C* **2019**, *7*, 8771.
135. Raut, N.C.; Al-Shamery, K. Inkjet printing metals on flexible materials for plastic and paper electronics. *J. Mater. Chem. C* **2018**, *6*, 1618.
136. Ibrahim, N.; Akindoyo, J.O.; Mariatti, M. Recent development in silver-based ink for flexible electronics. *J. Sci. Adv. Mater. Dev.* **2022**, *7*, 100395.
137. Sahu, A.; Aaen, P.H.; Lewandowski, A.; Shkunov, M.; Rigas, G.; Blanchard, P.T.; Wallis, T.M.; Devanbhaktuni, V.K. Robust microwave characterization of inkjet-printed coplanar waveguides on flexible substrates. *IEEE Trans. Instrum. Meas.* **2017**, *66*, 3271–3279.
138. Titirici, M.M.; White, R.J.; Brun, N.; Budarin, V.L.; Su, D.S.; Del Monte, F.; Clark, J.H.; MacLachlan, M.J. Sustainable carbon materials. *Chem. Soc. Rev.* **2015**, *44*, 250.
139. Lamanna, L.; Rizzi, F.; Bhethanabotla, V.R.; Vittorio, M.D. GHz AlN-based multiple mode SAW temperature sensor fabricated on PEN substrate. *Sens. Actuators A Phys.* **2020**, *315*, 112268.
140. Bell, D.L.T.; Li, R.C.M. Surface-acoustic-wave resonators. *Proc. IEEE* **1976**, *64*, 711–721.
141. Mengue, P.; Paulmier, B.; Hage-Ali, S.; Noirel, C.; Poncot, M.; Floer, C.; M'Jahed, H.; Shvetsov, A.; Zhgoon, S.; Nicolay, P.; et al. Temperature and strain SAW/BAW sensors on metallic substrates with RFID capability. *Smart Mater. Struct.* **2023**, *32*, 095017.
142. Yamazoe, N.; Miura, N. Environmental gas sensing. *Sens. Actuators B Chem.* **1994**, *20*, 95–102.
143. Kumar, A.; Kim, H.; Hanche, G.P. Environmental monitoring systems: A review. *IEEE Sens. J.* **1994**, *13*, 1329–1339.
144. Lee, C.Y.; Lee, G.B. Humidity sensors: A review. *Sens. Lett.* **2005**, *3*, 1–15.
145. Su, Y.; Ma, C.; Wu, H.; Luo, X.; Peng, Y.; Luo, Z.; Li, L.; Tan, Y.; Omisore, O.M.; Zhu, Z.; et al. Printable, highly sensitive flexible temperature sensors for human body temperature monitoring: A review. *Nanoscale Res. Lett.* **2020**, *15*, 200.
146. Herbon, A.; Levner, E.; Cheng, T.C.E. Perishable inventory management with dynamic pricing using time–temperature indicators linked to automatic detecting devices. *Int. J. Prod. Econ.* **2014**, *147*, 605–613.
147. Alemdar, H.; Ersoy, C. Wireless sensor networks for healthcare: A survey. *Comput. Netw.* **2010**, *54*, 2688–2710.
148. Gao, M.; Qiang, T.; Ma, Y.; Liang, J.; Jiang, Y. RFID-based microwave biosensor for non-contact detection of glucsose solution. *Biosensors* **2021**, *11*, 480.
149. Bibi, F.; Guilaume, C.; Gonard, N.; Sorli, B. A review: RFID technology having sensing aptitudes for food industry and their contribution to tracking and monitoring of food products. *Trends Food Sci. Technol.* **2017**, *62*, 91–103.
150. Zuo, J.; Feng, J.; Gameiro, M.G.; Tain, Y.; Laing, J.; Wang, Y.; Ding, J.; He, Q. RFID-based sensing in smart packaging for food applications: A review. *Future Foods* **2022**, *6*, 100198.
151. Machiels, J.; Appeltans, R.; Bauer, D.K.; Segers, E.; Henckens, Z.; Rompaey, W.V.; Adons, D.; Peeters, R.; Geiβler, M.; Kuehnoel, K.; et al. Screen printed antennas on fiber-based substrates for sustainable HF RFID assisted E-fulfilment smart packaging. *Materials* **2021**, *14*, 5500.
152. Mejias-Morillo, C.R.; Gbaguidi, A.; Kim, D.W.; Namilae, S.; Rojas-Nastrucci, E. UHF RFID-based additively manufactured passive wireless sensor for detecting micrometeoroid and orbital debris impacts. In Proceedings of the 2019 IEEE International Conference on Wireless for Space and Extreme Environments (WiSEE), Ottawa, ON, Canada, 16–18 October 2019; pp. 41–47.
153. Teckin, M.; Paker, S.; Bahadir, S.K. UHF-RFID enabled wearable flexible printed sensor with antenna performance. *Int. J. Electron. Commun.* **2022**, *157*, 154410.