RFID Technology for Food Industry 4.0: A Review of Solutions and Applications

Alessio Mostaccio *Graduate Student Member, IEEE*, Giulio Maria Bianco *Member, IEEE*, Gaetano Marrocco *Senior Member, IEEE*, Cecilia Occhiuzzi *Member, IEEE*,

Abstract—The emerging fourth industrial revolution is revolutionizing the food industry, which has historically been plagued by food waste and contamination. Several internet-of-things (IoT) technologies have been proposed for optimizing processes and reducing costs while improving health conditions and safety in food consumption. Among them, radiofrequency identification (RFID) has been considered from the beginning a key instrument, especially in food logistics and management. Many contributions and case studies from academia and industry demonstrated the strategic role and the impact on existing and future paradigms of food. The literature analysis in the present work suggests a growing interest in RFID to implement optimization procedures for food management and control. This review describes RFID employment in three pillars of the Fourth Generation of the Food Industry (FI4.0): Logistics, Sensing, and Green RFID. The logistics one comprises the most mature applications for RFID, such as cold-chain monitoring or product tracking. Food sensing, instead, is currently the most attractive research area for both industry and academia, so researchers are focusing their attention on detecting physical and chemical parameters through direct and indirect sensing approaches. Furthermore, the ever-increasing amount of electronic waste motivated the research community to provide sustainable tags to establish Green RFID devices. According to this literature review, RFID can foster the fourth industrial revolution in food, especially considering the emerging synergy with artificial intelligence and biodegradable/resorbable materials.

Index Terms—Edible, Food, Green, NFC, Radiofrequency Identification, Smart packaging.

I. INTRODUCTION

Food insecurity, malnutrition, and hunger are increasing worldwide, fostered by growing inequalities, conflicts, climate extremes, and economic shocks [1]. Outlooks [1] suggest that 8% of the world's population will still face hunger in 2030, and healthy diets could become unaffordable for more than 3.1 billion people.

Paradoxically, food production vastly exceeds the world population's needs, but due to mismanagement, food surplus evolves into food waste [2]. In 2021, the first "Food Waste Index" report of UNEP (United Nations Environment Programme) estimated that more than 930 million tonnes of food waste would have been produced annually [3]. Food quality threatens society as well. Every year, approximately $420,000$ people die after eating contaminated food; children are the most affected, with $125,000$ yearly deaths of people under 5 years old [4]. With the increased complexity of the food chain, foodborne illnesses have become a worldwide health issue affecting even high-income nations [4].

Furthermore, a relatively recent concern is related to the incorrect disposal of food packaging [5]. Optimized manage-

ment policies could have a relevant impact on both the environment [6] and the economy since, by reducing food surplus and waste, enterprises could gain up to 30% of additional profits [7]. Building more resilient and adequate food supply chains is hence essential to achieve optimal distribution [8] while reducing food and food packaging waste. Food quality monitoring commonly involves qualified personnel through sampling tests aiming at examining organoleptic properties detectable by human senses [9]. A systematic control, especially at the customer level, is still missing, and food assumption is left to the subjective and qualitative evaluation of the product.

In recent years, these global difficulties have also been investigated from a technological perspective by internet-of-things (IoT) experts. Platforms [10], which empower cyber-physical systems (viz., engineered networks of computational and physical components [11]) and dynamic, reconfigurable supply chains have been proposed for mitigating the main issues. The rationale behind the IoT perfectly fits the main challenge of the food industry, namely the simultaneous management and objective evaluation of a vast number of food products. The IoT paradigm is thus driving the fourth industrial revolution, gradually establishing industry 4.0 (I4.0) also in the food context. For instance, thanks to *smart packaging* (i.e., food packaging capable of wireless tracking [12], sensing [13], and even releasing substances [14]), perishable foods can be recognized when spoiling sooner than through human senses [15]. Indeed, non-destructing and low-cost techniques for food quality monitoring are currently being developed [9], [16], [17]. Furthermore, supply chain and packaging waste can be optimized by including in the packaging itself information about the product's transportation throughout its entire life through electronic and batteryless labels [18].

Currently, one of the bottlenecks in the adoption of the Food Industry 4.0 (FI4.0) over a large scale is the deployment of accurate, low-cost, and passive sensors. In this context, RFID (radiofrequency identification) technology could represent the missing physical layer for many of the required services since it assigns identifiers and connects existing things [19] with modest, or even null, power consumption, and at the cost of a few cents per item.

In the last decade, many examples of RFID solutions for the food sector have been proposed by both academia and industry, especially for logistics through low, high, ultra-high frequency, and even batteryless platforms [20], [21]. High-level architectures and theoretical benefits of deploying RFID have been systematically described and quantified [22], [23]. Food monitoring has been deeply investigated as well, often
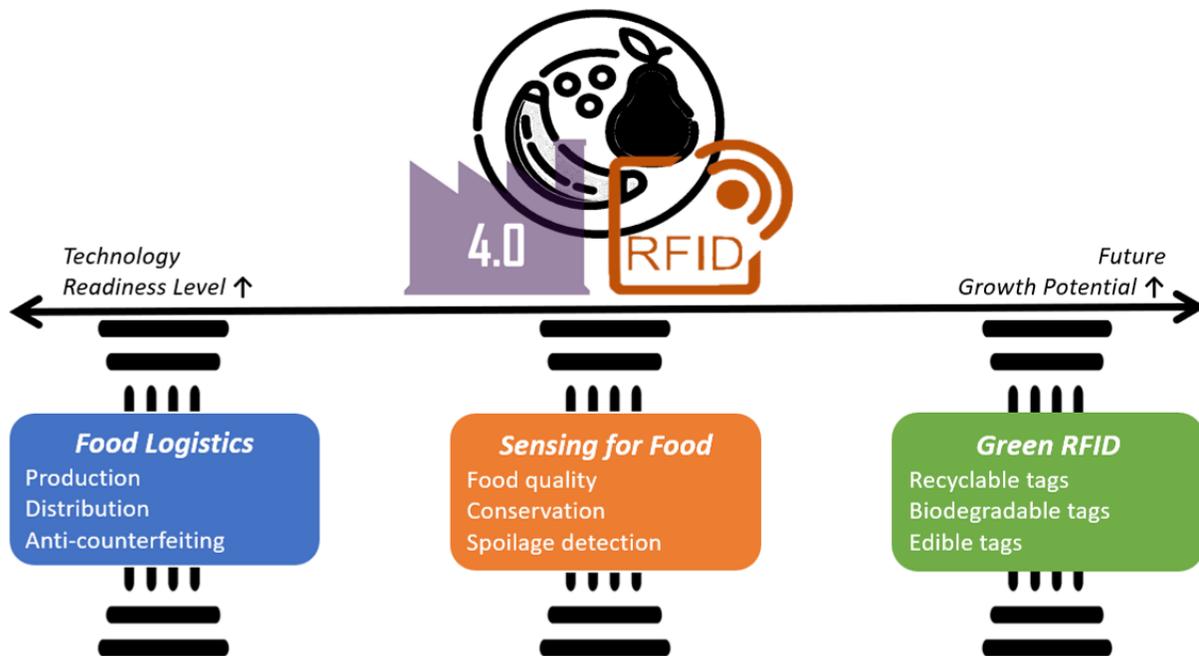
Fig. 1: Synopsis of the identified RFID research pillars in the Fourth Food Industry and their main applications.

by considering together RFID and other wireless and passive technologies [24].

In this paper, for the first time, applications of RFID in the food industry are systematically reviewed by considering all the operative platforms (NFC, UHF, and wideband) and all the most significant scenarios. Indeed, through scientometric trend analysis, this work surveys recent advances in RFID use for FI4.0 based on the following three pillars (Fig. 1).

1) *Food logistics* (first pillar). RFID for logistics is the most mature application pillar given that, since its first development, it has been employed for product tracking purposes.
2) *Food sensing* (second pillar), which can be achieved through dedicated sensors connected to the RFID tag or by using the tag's antenna itself as a sensor.
3) *"Green RFID"* (third pillar), a broad categorization encompassing all the emerging applications primarily aiming at reducing the environmental footprint of FI4.0.

The analysis includes contributions of the last eight years (ten years in some cases) and has the double objective of providing the reader with an operative landscape of the available technology as well as with a scientific landscape, such as to be acquainted with the most promising and emerging research fields.

The review is organized as follows. The methodology and the scientometric study are reported in Section II. Then, each research pillar is reviewed in a separate section. Section III explores the RFID hardware used in food logistics, and Section IV categorizes the food sensing devices based on the chemical/physical food parameters to be measured. Then, Section V introduces the Green RFIDs and some commercial tags of interest for that research line. Section VI ends the review by summarizing and discussing the findings.

II. METHODOLOGY AND TREND ANALYSIS

A. Scope and Methodology

The purpose of trend analysis is twofold; primarily, the scientometric tool allows us to identify the most recurrent keywords helping us to refine the document search. Then, the above results were employed to identify future developments on the topic. The scope of the literature review was limited to RFID applications concerning food products after preliminary filterings, like harvesting. Applications to agriculture [25], [26] and cattle farming [27] were not surveyed. Moreover, the sporadic works on low-frequency (LF) RFID for the food industry, (e.g., [28], [29]), were not included, given that they are mostly adopted for cattle identification and tracking.

High-level investigations analyses on the technology adoption [30] or architectures independent from the physical layer [31], [32] were excluded too. Two literature surveys were completed: the first search for a scientometric analysis of trends and topics, and the second, finer search for the in-depth study of reports selected based on the previous survey. The first search used the scientometric software ScientoPy [33] to search SCOPUS and Web of Science (WoS) databases. Afterwards, Google Scholar was employed too to include additional publications in the finer search. References for the in-depth study were selected based on their title and abstract, prioritizing works published after 2015. The WoS and SCOPUS databases were browsed on the 8th of February 2023 to generate the files to be used afterwards as input for the scientometric tool ScientoPy[1].

B. Scientometric Trend Analysis

After a literature search on the SCOPUS and WoS databases and based on the list of the 100 most used keywords, both

---

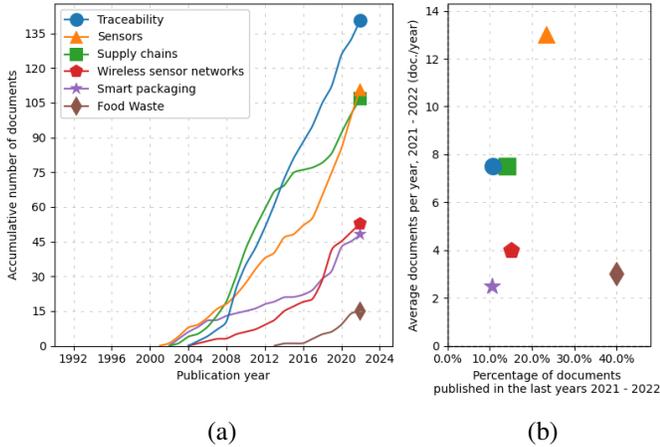[1]Available at: https://github.com/jpruiz84/ScientoPy

Fig. 2: ScientoPy processing of the literature data from WoS and SCOPUS. (a) The total number of published papers v.s. the publication year. (b) Average documents published per year v.s. the percentage of documents published over the total number of published papers (years: 2021-2022).

inserted by the authors and automatically assigned by the databases, 6 keywords related to different applications were identified: *i*) traceability, *ii*) sensors, *iii*) supply chain, *iv*) wireless sensor networks, *v*) smart packaging, and *vi*) food waste. The corresponding documents cover all the applications of RFID in FI4.0 (see Appendix A for further details on the trend analysis). Current research trends can be visualized based on the number of published works and the total existing papers. The evolution plot in Fig. 2a shows that research on RFID in the food industry started at the beginning of the 21st century with applications to supply chains, sensors, and smart packaging, soon followed by traceability uses. The first peak in research activity around 2010 regarded the typical RFID applications on supply chain and traceability. The second peak in 2018, instead, concerned sensing applications, with a contemporary renewal of interest in smart packaging. Instead, the first work on food waste was published in 2013, and the topic is still little investigated. When also considering the average number of documents published per year v.s. the percentage of the overall related published works (Fig. 2b), the scientific community appears to be currently shifting the attention from the first to the second pillar, while the research on waste management is still in its infancy like other researches aiming to reduce the environmental footprint of the FI4.0. Consequently, in the near future, we expect that the scholars' attention to the logistics pillar will continue fading while they will still focus on the sensing and green ones with the unprecedented growth of the latter.

III. LOGISTIC PILLAR

The logistic pillar includes all the systems and devices aiming at tracking the products and ensuring their integrity without resorting to sensing. It has the highest technology readiness level (TRL) among other RFID applications in the FI4.0, and several commercial components for traceability,

anti-tampering and quality assessment are already available (Table I). For each category, the papers are classified according to the operating frequency band. The "wideband" category comprises all the applications that do not includ RFID integrated circuits (ICs; i.e., chipless solutions, dielectric probes, resonators etc.). The TRL of the reports is also estimated and inserted in the table in their order of appearance in the "References" column.

A. Traceability

The term *traceability* refers to the capability of backward and forward tracking to determine the whole life history of a traceable resource unit (TRU) which can be defined as a physical entity corresponding to a unique identifier [62].

Tracking TRU is a classical employment of UHF RFID in retail since, unlike barcodes, no visual line of sight is needed, and multiple objects can be tracked simultaneously. The same architecture can also monitor the life history of food items, like cheese [35] (Fig. 3a), guaranteeing the origin of PDO (protected designation of origin) or PGI (protected geographical indication) foods [37].

HF RFID can be used similarly to UHF through check-points [40], potentially exploiting the NFC readers embedded in smartphones to follow TRUs even after the consumer distribution [45]. Wideband tags for inventory management were proposed in [47], but the need for a more sophisticated reader hampered their adoption.

Animal traceability can be achieved by any kind of tag [36], [39], [46] and, being RFID intrinsically scalable [63], traceability systems can be seamlessly integrated with the functionalities of quality assessment [44], anti-tampering [38], anti-counterfeiting [42], and quality control [43].

B. Quality Assessment

The most straightforward way to assess food quality is recurring the tracking history of the specific items [29], [51]. However, even a legitimate food item could be spoiled due to incorrect storage. For this purpose, HF labels providing real-time measurements of physical/chemical parameters by means of the buyer's smartphone have been proposed. An example of the measurement of the storage temperature [49], [50] is reported in Fig. 3b.

The food's quality can be assessed in a more effective way by recording the whole time-temperature history (TTH) of the TRU, though. The TTH includes all the temperature measurements performed during logistics operations with the corresponding timestamp and can indicate spoiled food even if it looks correctly preserved whilst the correct temperature was instead not always met. External temperature sensors connected to the tag's antenna can be used either in data-logging mode (i.e., the tag stores the TTH on its internal memory) [44], [48], [53] or by responding to continuous interrogation from the RFID reader [52]. Another approach is explored in [55], wherein a temperature-sensitive oil is placed onto a chipless tag. If exposed to higher temperatures, the oil melts partially, thus changing the response of the tag and providing a time-temperature indicator that could be integrated into a TTH information flow (Fig. 3c).

TABLE I: RFID in the FI4.0 logistics.

Application	Description	Band	References	Estimated Technology Readiness Level
Traceability	Backwards and forward tracking to determine the whole life history of a traceable resource unit (TRU).	UHF	[34] [35] [36] [37] [38] [39] [40] [41]	5, 6, 7, 7, 7, 8, 7, 8
		HF	[42] [43] [44] [40] [45] [39]	8, 6, 4, 7, 6, 8
		Wideband	[46] [47]	9, 6
Quality assessment	Monitoring of preservation status during the whole life-cycle (transportation, stacking and distribution) of the TRU.	UHF	[29] [48]	7 , 5
		HF	[49] [50] [51] [52] [53] [44] [54]	4, 4, 7, 6, 5, 4, 4
		Wideband	[55]	3
Anti-counterfeiting and anti-tampering	Assessment of both the packaging integrity and authenticity of the product inside it.	UHF	[56] [57] [58] [59]	5, 4, 6, 4
		HF	[60] [42]	5, 8
		Wideband	[61]	3

C. Anti-counterfeiting and Anti-tampering

The anti-counterfeit of food is also usually pursued through RFID and the "Track and Trace" approach, which consists of a software-based solution to track food along the entire supply chain, from the producer to the consumer [42]. Alternatively, cryptography can be exploited either standard or based on the physical characteristics of the tags, like the electromagnetic fingerprint [58]. However, cloning attacks can defeat the most basic track-and-trace systems. Proposed countermeasures against cloning were the encoding of encrypted identifiers in the IC's user memory [60] and the use of blockchain [59]. Yang *et al.*, instead, exploited the intrinsic variability of the manufacturing process of chipless tags to create random, unique, and unclonable identifiers [61].

Tampering of food can be detected by checking packaging integrity. Hence, anti-opening sensors changing the response of the tag if they are unfolded can be integrated into food packaging to prevent the customer from buying opened food containers [56], [57] (Fig. 3d). Obviously, the anti-tampering feature could be embedded in a tracking system to obtain information about the time of opening.

IV. SENSING PILLAR

The application of RFID technology to the sensing of the food's status is the most challenging task despite attracting the major attention of the researchers. It is characterized by a medium TRL since most of the applications come from academic research; there are even some pilot experimentations in industrial sites [64], [65], though.

This Section reports the most recent applications and, at the same time, collects the different strategies employed in literature according to the target indicator. With reference to Table II, a preliminary clustering criterion is about the class of analyte. We distinguish the measurement of chemical parameters (e.g., pH, biogenic amines or ethylene) from the physical ones (e.g., pressure, variation of electromagnetic properties or temperature). The latter is indirectly linked to spoilage phenomena but are more easily captured so that their employment lowers the implementation cost of the RFID sensing infrastructures. In particular, the physical parameters can be targeted by exploiting the *sensor-less* approach [66], wherein the antenna itself is used as the sensing transducer by collecting variations of its radiofrequency properties in reaction to changes in the permittivity of the tagged object. As in the previous Section, state of the art has been classified according to the frequency band and highlighting in brackets
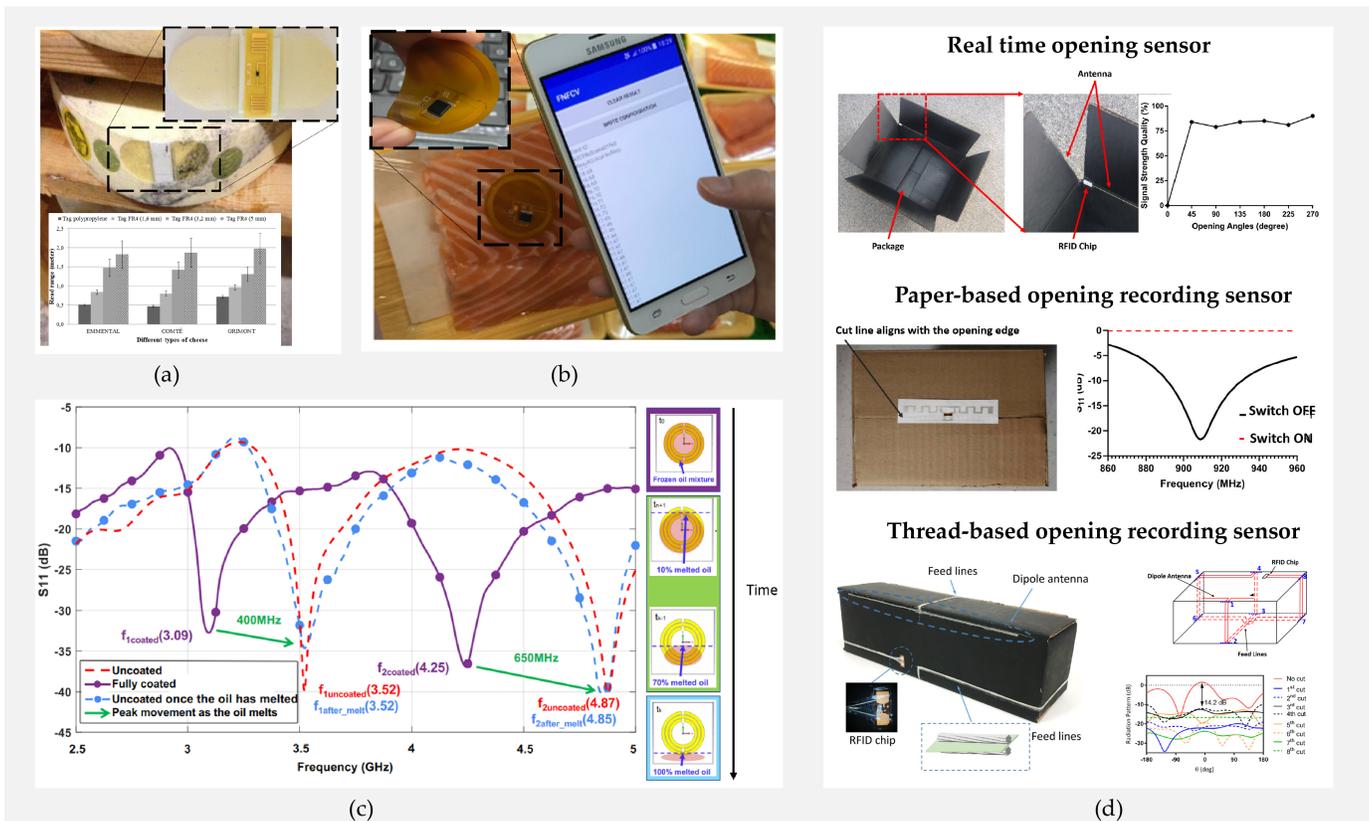
Fig. 3: Example of RFID devices and systems for food tracing and quality assessment. (a) Embedded tag in a cheese wheel in the top right inset. According to the read range and the antenna substrate, different kinds of cheese can be distinguished (adapted from [35]). (b) Flexible NFC tag for organic food quality and storage temperature detection. The system is able to detect either opening or damage to the packaging (adapted from [49]). (c) Chipless tag for cold chain monitoring. Each tag is covered by a layer of frozen oil which melts as the temperature increase (right inset). Oil melting determines a frequency shift of the reflection coefficient of the interrogating antenna (adapted from [55]). (d) Employment of UHF RFID tags as real-time opening sensor [57].

the number of the proposed solution for each parameter.

A. Chemical Parameters

The most accurate and reliable way to determine the preservation status of food is to monitor the concentration of analytes related to degradation. As a matter of fact, the presence of amines and bacteria is generally linked to spoilage [100]. The oxygen inside the packaging is responsible for triggering the browning mechanism [101] while, instead, ethylene is strongly correlated to fruit ripening. For example, a rapid increment in the analyte concentration corresponds to the beginning of the ripening stage for climacteric fruits [102]. The key feature of this strategy is its accuracy and the possibility of local monitoring. The possibility of immediately identifying premature fruits could therefore avoid the wastage of all foods stored in the same container preventing ripening during transportation and storage [103]. This method requires a complex hardware architecture. The evaluation of the analytes' concentration is generally performed by means of external sensors [71]. This implies an integration among the functional units (sensing, communication, and control) of the device [70], raising the overall cost and size.

Chemical sensing is achieved through materials that are sensitive to the target analyte. Such materials can be arranged as loads for the tag's antenna (e.g., interdigitated capacitors) or can be connected to special ICs provided with analog front-ends [104]. The variation of turn-on power, i.e., the minimum received power required to activate the RFID IC, can be correlated with bacteria [67] or gases (O_2, CO_2 and ethanol) concentration [68] (Fig. 4). For instance, the target analyte interacts with a layer of wheat gluten, chemically loading the tag, so to cause the detuning of the antenna [68].

The chemical loading of interdigitated capacitors connected to NFC tags is the most common tool to achieve sensing functionalities (Fig. 5a). Capacitance changes can be simply induced by the variation of the chemical concentration of the substrate where the capacitor is placed, like in the case of water contamination. In [75], indeed, Qian *et al.* estimated the concentration of total dissolved solids (TDS) in water, like pesticides, lead, arsenic, and fluoride. By connecting the NFC front-end to a parallel plate capacitor, the TDS was estimated with high accuracy when compared to commercial gold standards. Nevertheless, conductive polymers such as polyaniline (PANi) [70], poly(3,4-ethylenedioxythiophene)

TABLE II: RFID for food sensing. In the "Target" and "Sensor Type" columns, the numbers between parentheses indicate the number of works targeting the given parameter/employing that sensor. Not all the reports specify the sensor type. Different parameters/sensors are separated by commas, and references are separated according to the target.

Measurand class	Type of sensor	Band	Target	References	Estimated Technology Readiness Level
Chemical	Electrochemical (1), Potentiometric (4) Dielectric (3) Resistive (3), Capacitive (6)	UHF	Bacteria (1), Gas concentration (1)	[67], [68]	6, 6
		HF	Ammonia/amine (6), Potassium (1), Total Dissolved Solids - TDS (1), pH (1)	[69] [70] [71] [56] [72] [73], [74], [75], [76]	6, 4, 7, 6, 4, 4, 4, 6, 5
		Wideband	Ammonia/amine (2), pH (2), Ethanol (1), CO_2 (1)	[77] [78], [79] [80], [81], [82]	6, 6, 3, 4, 4, 6
Physical	Resistive (3), Barometric (2), Dielectric (12), Weighting (1)	UHF	Pressure (2), Ripening (5), Liquid content (1)	[65] [83], [84] [85] [64] [86] [87], [88]	5, 6, 8, 7, 8, 6, 2, 3
		HF	Pressure (3), Temperature (2), Ripening (2)	[89] [90] [91], [92], [76] [93]	4, 6, 7, 6, 5, 6
		Wideband	Temperature (1), Humidity (2), Protected Geographical Indication (5)	[94], [82] [21], [95] [96] [97] [98] [99]	5, 6, 5, 3, 3, 3, 2, 3

polystyrene sulfonate (PEDOT:PSS) [56], or carbon nanotubes (CNTs) [69] are commonly employed as chemical loads since their interaction with amine molecules causes the variation of their electrical properties.

Sensors can also be integrated into NFC tags for monitoring the level of ammonia (Fig. 5b) [56], [73] or potassium ions [74]. The inductive NFC coupling can better energize the microchips, allowing more complex sensing (e.g., chronoamperometry [104] or potentiometry [76]), which can be too power-hungry for UHF circuits.

Passive, chipless tags are significantly cheaper than chipped ones. They generally act as resonators whose radar cross section (RCS) is modulated by the concentration of analytes. These tags are, therefore, chemically loaded to sense different chemical parameters, such as, for example, the pH [80]. One of the major concerns regarding chipless tags is the isolation of their backscattered signal from that of the surrounding environment. Accordingly, Raju and Bridges [78], [79], developed an RCS-based depolarizing tag able to perform amine potentiometric sensing only by employing a varactor (Fig. 5c). In order to distinguish the tag response, they employed both the co-polarized and cross-polarized components of the scattered signal.

Another possible strategy to sense analytes without any IC is to employ a near-field probe, generally a coil that couples with a resonator. The target analyte's concentration causes the probe's detuning; so, by connecting it to a VNA, the concentration of the analyte is retrieved by analysing the frequency shift of the probe's reflection coefficient [77], [81].

Though the environment does not affect the measurement in this case, the method requires expensive hardware, and it is difficult to scale up.

B. Physical Parameters

The quality assessment can also be achieved through the monitoring of physical parameters. In fact, spoilage is related to the growth of bacteria, causing the increment of CO_2 concentration and, thus, of the pressure inside sealed packaging. Ripening, instead, is generally due to modifications of enzymes, sugar and water contents [84], which leads to complex permittivity and/or weight changes. Finally, since the food preservation status is affected by the storage conditions, either direct or indirect temperature and RH tracking may be employed as quality indicators.

Therefore, physical sensing employs ICs with internal sensors or analog-to-digital front-ends to connect a variety of external low-power transducers (e.g., resistive or NFC chemical sensors) [105]. Moreover, in the case of digital external sensors [76], [83], [93], the harvested RF energy powers microcontroller units necessary to control the acquisition. Even though the hardware is relatively complex and the accuracy is lower, collecting physical indicators is thus generally easier than the chemical ones. In this context, UHF ICs are more commonly used than their HF/NFC counterpart.

Starting from these considerations, Abdelnour *et al.* [65] evaluated the ripening status of Swiss-type cheese. This product is generally kept inside closed plastic foils so that the swelling process can be detected by connecting a resistive
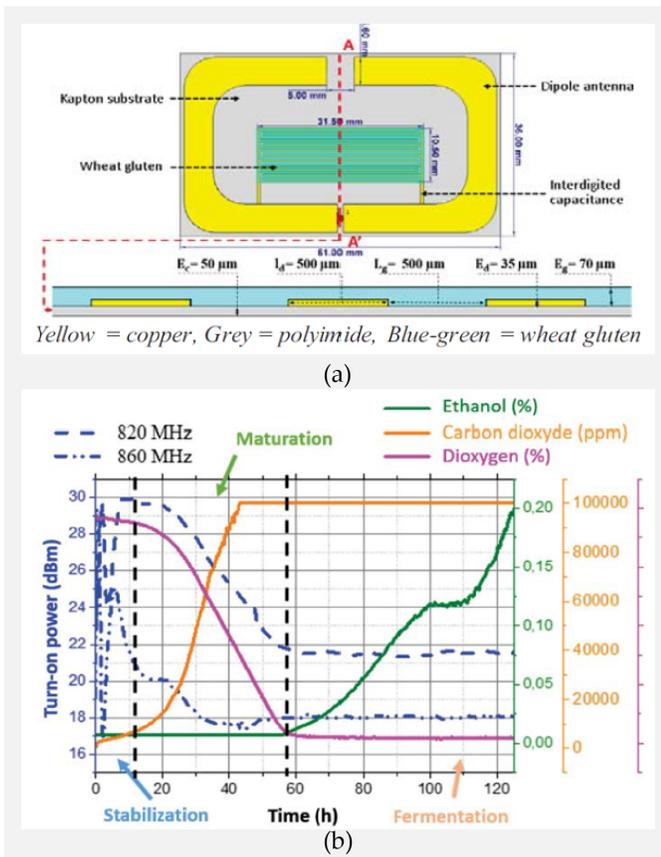
(a)

(b)

Fig. 4: RFID tag for monitoring food quality. The antenna is connected to an interdigitated capacitor whose active layer is wheat gluten. (a) Layout of the sensor tag. (b) The impact of different gasses (ethanol, carbon dioxide and dioxygen) on the turn-on power (adapted from [68]).
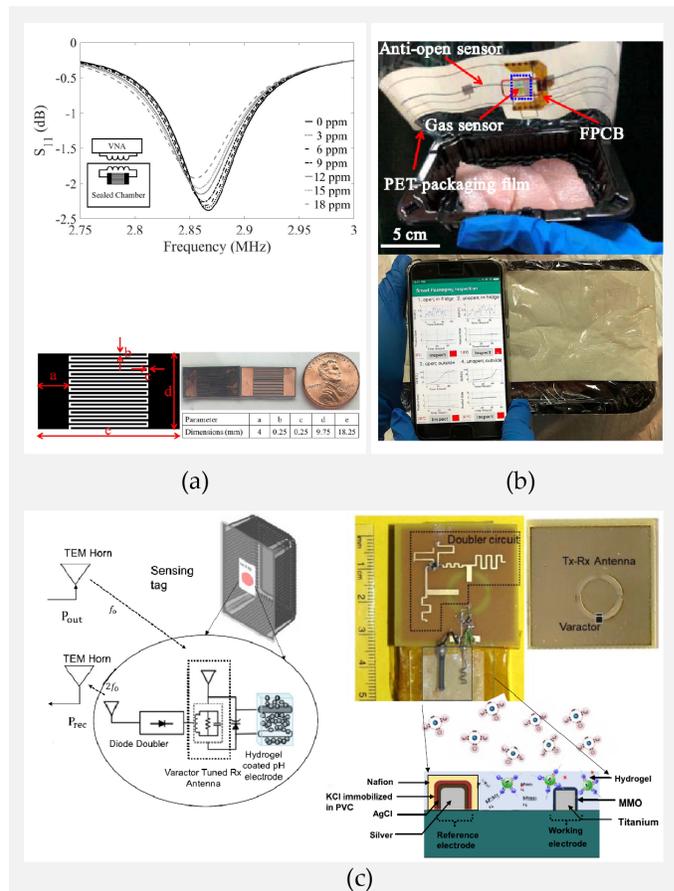

Fig. 5: RFID tags for chemical sensing. (a) Impact of the biogenic amines on the resonance frequency of the tag reported in the bottom left inset (adapted from [70]. (b) Smart packaging POC developed in [56]. The system is capable of detecting opening events as well as variations of amine concentration and sending the data on the smartphone. (c) Schematic representation of the tag proposed in [78]. The carrier frequency is doubled by a frequency doubler circuit controlled by a potentiometric sensor and a varactor.

sensor to the outer shell of the foil. In fact, the variation of pressure is converted into an increment of resistance, and consequently, the corresponding CO_2 concentration raised by the ripening cheese is estimated.

Different dielectric probing methods have been proposed either to assess the food quality [95], [99] or to verify the Protected Geographical Indication (PGI) [96]–[98].

A change in the dielectric properties of the target is expected, causing the antenna to be the sensor itself [84], [87]. Several metrics, such as the RSSI, the phase and the turn-on power, can be extracted from the RFID link. All of these quantities are related to the impedance matching of the antenna; thus, the variation of the dielectric properties of the substrate can affect it. Artificial intelligence algorithms can be trained to discriminate the ripening status of climacteric fruits [64], [85] (Fig. 6a). Similarly, in [88], the authors evaluated different arrangements of RFID tags to study the impact of weak coupling between the antennas and the material underneath based on the spectrum of the backscattered signals.

Smart packaging applications require for their large-scale deployment low manufacturing cost, ease of use for the final user and automatic and accurate interrogation procedures. Although colorimetric labels (namely labels subjected

to colour changes in case of chemical reactions like spoilage) can provide the above two features, they need a manual or semi-automatic visual inspection. Unfortunately, variable environmental conditions, and above all, illumination ones, may affect the measure. Hence, the authors of [92] merged RFID and colorimetric technologies to make the best of both systems. Here, the information is encoded in the shift of the resonance frequency due to the variation of the chemical concentration sensed by the label. Miscioscia et al., instead, printed an interdigitated capacitor upon a colorimetric critical temperature indicator (CTI); the former was then connected to an NFC coil. When the temperature overcomes a threshold, the chemical reagent, i.e., black blotting paper, melts, changing the label colour from white to black (Fig. 6b). This induces a variation of the dielectric properties of the label itself, causing a capacitance variation as well. In this way, the encoding of a chemical reaction into a shift of the resonance frequency was achieved.
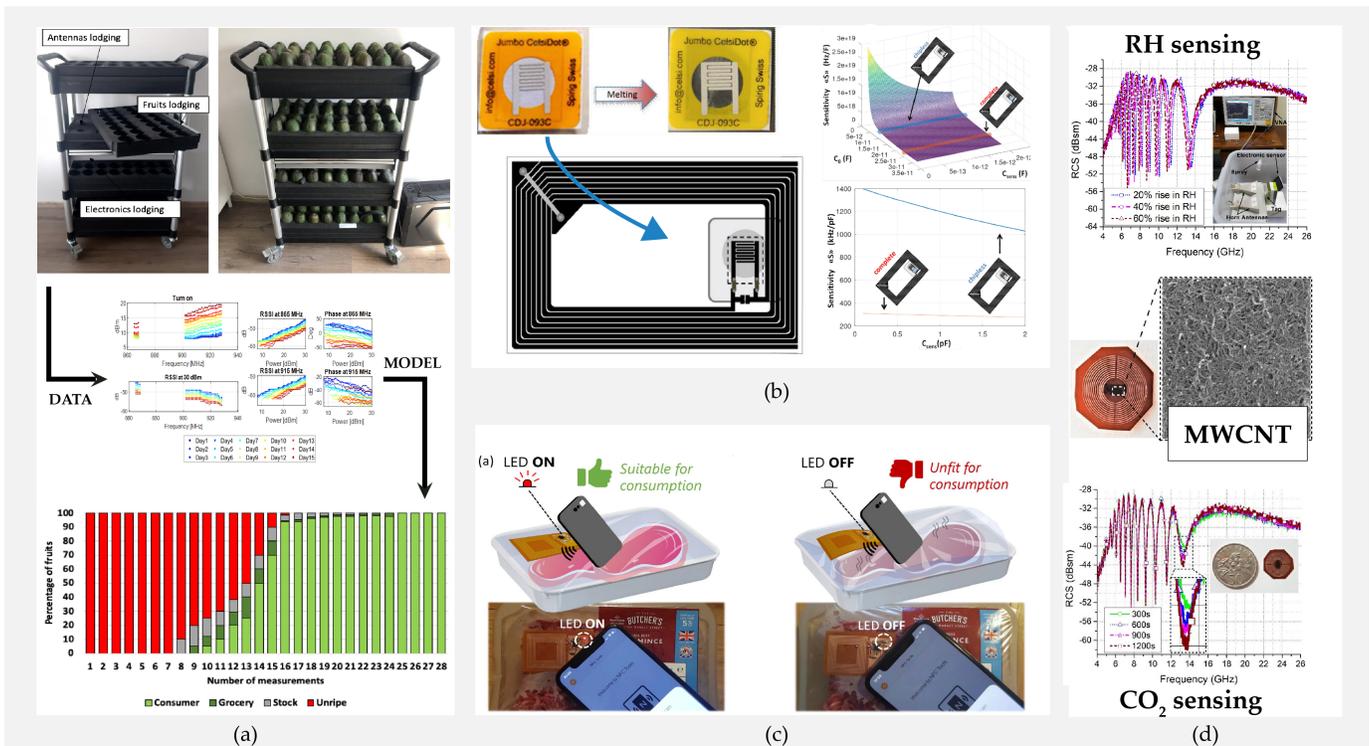
Fig. 6: RFID systems for food quality control. (a) Smart ripening system. Each avocado fruit is RFID-tagged to generate data that feed machine learning algorithms. The algorithms predict the ripening status of the fruit, allowing the modification of the storing conditions (adapted from [85]. (b) Critical temperature indicator proposed in [92]. The sensor (top inset) changes its colour when overcoming the critical temperature, modifying, in turn, the capacitance. The capacitance determines the shift of the resonance frequency. The sensitivity of the system, both considering the IC and neglecting it, is reported in the right inset (c) NFC label for detecting altered food packaging through strain. The status of the food is indicated by a LED powered through the NFC magnetic field [90]. (d) Chipless tag capable of detecting variations of both the RH level and of the CO_2 concentration (adapted from [82]).

Similarly, by means of a LED and an NFC tag, researchers [89], [90] developed an RFID system capable of providing information about the preservation status of food both visually and electronically. The authors employed a flexible polydimethylsiloxane (PDMS) membrane provided with micro-channels of a conductive polymer (PEDOT:PSS) that were drop cast as a sensing layer. Food swelling produces a strain over the packaging foil, which induces a variation in the resistance of the sensor. Accordingly, the voltage across the LED varies, and so does its brightness (Fig. 6c). Moreover, PEDOT:PSS is temperature sensitive; hence the sensor has been demonstrated to act as a critical temperature indicator too.

Chipless solutions have been explored as well. For example, a flexible complementary split ring resonator acting as a customizable critical temperature indicator is described in [94]. The authors manufactured a PDMS membrane including three slotted circular microchannels filled with a liquid metal alloy, namely Eutectic Gallium Indium. Then, the gaps were filled by a mixture of two different frozen commercial oils so that when the threshold temperature is reached, the compound melts, and the dips in the RCS shift toward lower frequencies. By changing the mixture ratio between the oils, two threshold temperatures (4 °C and 8 °C) were achieved.

Finally, in [82], a tag for both physical and chemical sensing was developed by integrating an array of radiating slots on Polyimide (PI) with multi-wall carbon nanotubes (MWCNTs). The substrate acts as an RH sensor shifting the frequency of each dip in the RCS; the chemical composition of MWCNTs, instead, is affected by the CO_2 concentration, modifying the amplitude of the dip in the spectrum accordingly (Fig. 6d).

V. GREEN RFID PILLAR

"Green RFID" is a broad term used in general to refer to environmentally friendly RFID devices and systems [125]. In the context of FI4.0 and within the scope of this article, all the applications aiming at a more sustainable food industry that are not included in the logistic or detection pillars belong to Green RFID and are grouped in Table III. Although academic research on Green RFID for food began in early 2010s, just a few tags have finally reached the commercialization and certification stages, as detailed next.

A. Tags for Recycling

1) Tags made of recyclable materials: By definition, recyclable tags must not hinder the recycling process of the object they are attached to so that the recyclability of an RFID

TABLE III: Green RFID in the Fourth Food Industry

Type	Description	Band	References	Estimated Technology Readiness Level
Tags for Recycling	Capability of tags to be fully integrated inside the packaging and be recycled together or to assist the recycling process	UHF	[106]	3
		HF	[107]	2
		Wideband	[108] [109]	2, 2
Biodegradable and Edible	Capability to be quickly degraded by the environment or completely absorbed during the digestion	UHF	[110] [111] [112] [113] [114] [115] [116] [117] [118] [119]	3, 3, 3, 3, 3, 1, 3, 2, 1, 3
		HF	[120] [119]	3, 3
		Wideband	[117] [121]	2, 4
Commercial-off-the-shelves	Recyclable and biodegradable tags on the market at the time of writing	UHF	[122] [123]	9, 9
		HF	[124] [123]	9, 9

tag depends on both the materials of the tagged item and the tag's antenna. In the food industry, smart labels are generally embedded in the packaging rather than in the food item. In this way, indeed, *i*) any local degradation of the tagged piece of food is avoided, *ii*) the consumer perception of the latter is kept unchanged, and, finally, *iii*) a circular economy of the label and the packaging is granted at the same time.

All the components of a tag, namely the IC, the conducting trace forming the antenna and the substrate, should be recyclable. Concerning the antenna, the absence of metal can foster the recyclability of the tagged object with respect to classic tags' antennas. Hence, Marque *et al.* [106] proposed a semi-transparent and non-metallic polymer-based paste (PCT-2.2 by TICON) that uses water as a diluent. In [107], instead, two nanosilver inks ("Orgacon SI-P2000" by Agfa-Gevaert and "Loctite ECI 1011" by Henkel) were tested. Big efforts were also made for the development of recyclable substrates as the same authors compared 76 fiber-based substrates to manufacture recyclable RFID tags for smart packaging made of cardboard. In the end, the wood-free graphic paper "Magno Satin" was used to create recyclable prototypes.

2) Tags to assist recycling: In addition to logistics using recyclable tags, RFID labels could actively assist in recycling by returning information on the item's material. To this end, chipless tags are currently being investigated to discriminate different types of plastics based on the EM responses (Fig. 7a). Preliminary results reached a discrimination accuracy higher than 90% when discriminating two plastics [108]. More advanced work on the discrimination of glass and seven plastics

can be found in [109].

B. Biodegradable and Edible

Biodegradable RFID tags do not need specific waste processing, thus allowing minimisation of the environmental footprint. In the vision of the FI4.0, they could allow the tracking and tracing of individual pieces of food, and they could degrade with the tagged food itself. The simplest works in this direction focus on biodegradable substrates and neglect the conductor since it is a smaller portion of the tag. Thanks to its availability, paper is the most exploited bioresorbable substrate [111], [115], [117], and it can perform similarly to the widely-employed FR-4 substrates [117]. 3D-printed substrates using biodegradable polymers are another possible option for such RFID tags [110], [113], [114]. Concerning the conductors, bioresorbable copper-based paint [112] and conductive zinc ink [116] are two identified solutions (Fig. 7b). In particular, Gopalakrishnan *et al.* [121] confirmed the feasibility of using zinc as a biodegradable conductor for RFID tags.

Alternatively, edible RFID transponders have been demonstrated to be a valid solution for FI4.0. Yet, despite the recent advances concerning edible and ingestible electronics [126]–[128], research on these devices is still limited. An ingestible dual-frequency tag to be inserted in pills for checking medication compliance was proposed in [119], but no digestible prototype was presented or validated. Tao *et al,* in [120], instead, describe a fabrication technique for using edible gold and silk for HF tags. The technique can also be applied to different frequencies. Even if the presented
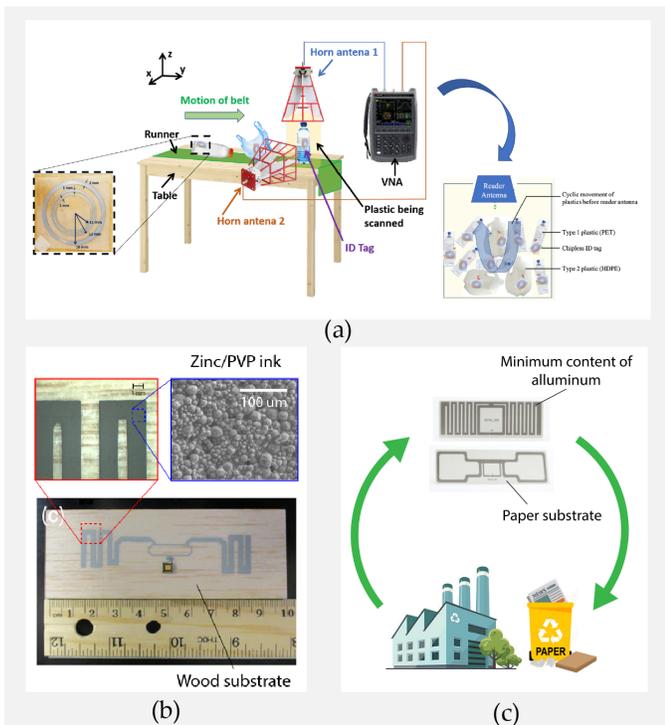
Fig. 7: Green RFIDs. (a) Chipless tag for plastic material recognition based on the RCS (adapted from [108]). (b) Bioresorbable RFID tag primarily made of conductive zinc ink and balsa wood as a substrate. Adapted from [116]. (c) Green RFID tags fabricated with paper and a small content of aluminium suitable to be recycled within the paper recycling cycle (adapted from [123]).

prototypes are indeed digestible, only chipless RFID tags could be manufactured in this way since digestible RFID microchips do not exist currently.

C. Commercial-off-the-shelves Tags

By virtue of its practical and commercial value, the limited research on Green RFIDs has already hit the markets even though a small set of tags are available at present. Fully recyclable UHF and HF labels exploiting minimal metal content to comply with the paper recycling regulation are yet on the market [122], [123] (Fig. 7c). Therefore, they can be applied to any paper-based food packaging without hindering recyclability. Even though such tags can degrade after 2 years of dispersion in the environment, they cannot be considered biodegradable according to current definitions, which enforce a stricter time limit (more information in [129]). On the contrary, the ECO RFID line of labels in [124] obtained multiple certifications of biodegradability, compostability, and recyclability.

VI. Conclusion

The state of the art of RFID research and applications to the food life-cycle can foster logistics, sensing, and eco-sustainability goals of the digital transformation of the food industry. Despite being still a niche, this research field is

TABLE IV: Average, maximum and minimum TRL for each pillar based on the reviewed papers.

Pillar	Average $\pm$ std	Maximum	Minimum
Logistic	5.72 ± 1.60	9	3
Sensing	4.97 ± 1.66	8	2
Green	3.58 ± 2.46	9	1

rapidly growing, especially concerning sensing and smart packaging. Radiofrequency identification and sensing will play a crucial role in FI4.0 in the next years due to the maturity of the technology for logistics and the promising tests for sensing. Table IV reports the TRL for the three pillars reviewed in the pages above; for each reviewed paper, a TRL was estimated so that the average technology readiness of the pillar could be evaluated. Despite including some COTS devices, the Green pillar is confirmed to be the least investigated one, given that most papers concern fundamental research on biodegradable material for antenna design.

There are naturally still open issues. First of all, the highest-TRL pillar, namely the logistic one, could be exploited further. The emerging synergy with machine learning and artificial intelligence [130] can boost the adoption of RFID thanks to the additional features it can provide, for instance, estimating if some food products are entering or leaving the warehouse [131]. The pillars having lower TRL have yet to demonstrate their practical feasibility beyond theoretical soundness. For instance, most of the reviewed sensing approaches require electronic circuitry whose cost can be amortised by the vendor provided that the items' price is raised or an adequate waste reduction is achieved. This practice is probably possible only with expensive foods, i.e., meat and fish, while different solutions should be found in the case of low-cost food. Furthermore, the transduced signal from the sensor generally fluctuates within the same class of food, affecting thus the sensor's repeatability. As a consequence, the identification of objective metrics is strongly hindered. Biodegradable components also have yet to be fully assessed, and the next future works can exploit the synergy with the current research in bioresorbable materials driven by the advances in medical engineering [132]. Overall, in the next few years, we expect a surge of RFID academic proofs-of-concept and industrial tests regarding the food that will boost the development of reliable hardware and software solutions for large-scale adoption.

APPENDIX A
TREND ANALYSIS DETAILS

The search strings were used to collect as many works on RFID related to the three research pillars as possible, as reported in Table V. The first screening omitted the documents that were not journal or conference papers, reviews, or articles soon to be published. The second screening eliminated duplicates between the SCOPUS and WoS lists, and the final merge removed duplicated entries between different keywords. 2646 records were found for the subsequent trend analysis, and most of the keywords found in the complete list of 100 most used keywords were not subsequently considered since most of them were application-independent (like "RFID"), duplicates (like "supply chains" and "supply chain"), or too generic (like "labels"). The "food waste" keyword was not among the 100 most used and was inserted to represent the Green RFID emerging pillar. The final subset of reports selected using the 6 keywords (see Table V again) was finally employed to investigate the current trends in Fig. 2.

TABLE V: Literature searches screened through ScientoPy. Search strings: ("RFID" OR "Near Field Communication")...

Search terms	Initial search	First screening	Second screening	Merge
... AND "food"	1995	1840	1320	-
... AND "packaging"	1883	1690	1331	-
... AND ("grocery" OR "catering")	183	169	125	-
... AND "spoilage"	103	101	68	-
... AND "restaurant"	92	89	72	-
... AND "biodegra-dable"	62	56	37	-
... AND "edible"	17	11	11	-
Total	4335	3956	2964	2646

REFERENCES

[1] Food and Agriculture Organization of the United Nations, "The state of food security and nutrition in the world: Repurposing food and agricultural policies to make healthy diets more affordable," Rome, Italy. Accessed: 6 October 2022. [Online]. Available: https://www.fao.org/3/cc0639en/cc0639en.pdf.

[2] R. Hopfenberg, *Population density and redistribution of food resources*, 2019.

[3] United Nation Environment Programme, "Food Waste Index: Report 2021," Rome, Italy. Accessed: 6 October 2022. [Online]. Available: https://wedocs.unep.org/bitstream/handle/20.500.11822/35280/FoodWaste.pdf.

[4] World Health Organization, "Foodborne diseases," Rome, Italy. Accessed: 8 July 2022. [Online]. Available: https://www.who.int/health-topics/foodborne-diseases#tab=tab_2.

[5] European Economic and Social Committee, "Recycling food packaging & food waste in plastic revolution," Brussel, Belgium, 2020. Accessed: 8 July 2022. [Online]. Available: https://www.eesc.europa.eu/de/our-work/publications-other-work/publications/recycling-food-packaging-food-waste-plastics-revolution.

[6] Food and Agriculture Organization of the United Nations, "The state of food and agriculture: Making agrifood systems more resilient to shocks and stresses," Rome, Italy. Accessed: 10 July 2022. [Online]. Available: http://www.fao.org/3/cb4476en/cb4476en.pdf.

[7] The Waste and Resources Action Programme, "Financial implications for farm enterprises of reducing food surplus and waste," Oxfordshire, United Kingdom. Accessed: 8 July 2022. [Online]. Available: https://wrap.org.uk/resources/report/financial-implications-farms-reducing-food-surplus-and-waste.

[8] Food and Agriculture Organization of the United Nations, "The state of food and agriculture," Rome, Italy. Accessed: 10 July 2022. [Online]. Available: https://www.fao.org/3/i2050e/i2050e.pdf.

[9] M. Mohd Ali, N. Hashim, S. K. Bejo, and R. Shamsudin, "Rapid and nondestructive techniques for internal and external quality evaluation of watermelons: A review," *Scientia Horticulturae*, vol. 225, p. 689 – 699, 2017.

[10] Y. Yin, K. E. Stecke, and D. Li, "The evolution of production systems from industry 2.0 through industry 4.0," *International Journal of Production Research*, vol. 56, no. 1-2, p. 848 – 861, 2018.

[11] D. G. Rosado, A. Santos-Olmo, L. E. Sánchez, M. A. Serrano, C. Blanco, H. Mouratidis, and E. Fernández-Medina, "Managing cybersecurity risks of cyber-physical systems: The marisma-cps pattern," *Computers in Industry*, vol. 142, p. 103715, 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0166361522001129

[12] M. Biegańska and W. Kozak, "Contemporary technologies used for product traceability and quality control," in *Current Trends in Commodity Science. Challenges in Food Development and Processing*. Poznań, Poland: Poznań University of Economics and Buisness, 2017, pp. 135–148.

[13] C. M. Fernandez, J. Alves, P. D. Gaspar, T. M. Lima, and P. D. Silva, "Innovative processes in smart packaging. a systematic review," *Journal of the Science of Food and Agriculture*, 2022.

[14] S. Ullah, M. Hashmi, J. Lee, J. H. Youk, and I. S. Kim, "Recent advances in pre-harvest, post-harvest, intelligent, smart, active, and multifunctional food packaging," *Fibers and Polymers*, vol. 23, no. 8, p. 2063 – 2074, 2022.

[15] S. B. Hashim *et al.*, "Smart films of carbohydrate-based/sunflower wax/purple chinese cabbage anthocyanins: A biomarker of chicken freshness," *Food Chemistry*, vol. 399, 2023.

[16] P. D. C. Sanchez *et al.*, "Emerging nondestructive techniques for the quality and safety evaluation of pork and beef: Recent advances, challenges, and future perspectives," *Applied Food Research*, vol. 2, no. 2, 2022.

[17] A. Mostaccio, G. M. Bianco, S. Amendola, G. Marrocco, and C. Occhiuzzi, "Rfid for food industry 4.0 - current trends and -monitoring of fruit ripening," 2022.

[18] E. Abad, F. Palacio, M. Nuin, A. G. De Zarate, A. Juarros, J. M. Gómez, and S. Marco, "Rfid smart tag for traceability and cold chain monitoring of foods: Demonstration in an intercontinental fresh fish logistic chain," *Journal of food engineering*, vol. 93, no. 4, pp. 394–399, 2009.

[19] C. Occhiuzzi, S. Amendola, S. Nappi, N. D'Uva, and G. Marrocco, "RFID technology for industry 4.0: Architectures and challenges," 2019, p. 181 – 186.

[20] F. Dabbene, P. Gay, and C. Tortia, *Radio-Frequency Identification Usage in Food Traceability*, 2016.

[21] P. Fathi, N. C. Karmakar, M. Bhattacharya, and S. Bhattacharya, "Potential chipless rfid sensors for food packaging applications: A review," *IEEE Sensors Journal*, vol. 20, no. 17, p. 9618 – 9636, 2020.

[22] Z. Zou, Q. Chen, I. Uysal, and L. Zheng, "Radio frequency identification enabled wireless sensing for intelligent food logistics," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 372, no. 2017, 2014.

[23] F. Bibi, C. Guillaume, N. Gontard, and B. Sorli, "A review: RFID technology having sensing aptitudes for food industry and their contribution to tracking and monitoring of food products," *Trends in Food Science and Technology*, vol. 62, p. 91 – 103, 2017.

[24] R. Raju, G. E. Bridges, and S. Bhadra, "Wireless passive sensors for food quality monitoring: Improving the safety of food products," *IEEE antennas and propagation magazine*, vol. 62, no. 5, pp. 76–89, 2020.

[25] A. Khanna and S. Kaur, "Evolution of internet of things (iot) and its significant impact in the field of precision agriculture," *Computers and Electronics in Agriculture*, vol. 157, p. 218 – 231, 2019.

[26] L. Ruiz-Garcia and L. Lunadei, "The role of RFID in agriculture: Applications, limitations and challenges," *Computers and Electronics in Agriculture*, vol. 79, no. 1, p. 42 – 50, 2011.

[27] J. Zhao, A. Li, X. Jin, and L. Pan, "Technologies in individual animal identification and meat products traceability," *Biotechnology and Biotechnological Equipment*, vol. 34, no. 1, p. 48 – 57, 2020.

[28] A. Arnaud and G. Costa, "Ultra low-cost sensors using rfid standards for data collection, for iot systems in food production and logistics," 2020.

[29] P. Barge, A. Biglia, L. Comba, D. R. Aimonino, C. Tortia, and P. Gay, "Radio frequency identification for meat supply-chain digitalisation," *Sensors*, vol. 20, no. 17, p. 1 – 17, 2020.

[30] E. Rajo-Iglesias, I. Cuiñas, R. Newman, M. Trebar, L. Catarinucci, and A. A. Melcon, "Wireless corner: RFID-based traceability along the food-production chain," *IEEE Antennas and Propagation Magazine*, vol. 56, no. 2, p. 196 – 207, 2014.

[31] L. Hu, C. Xiang, and C. Qi, "Research on traceability of cold chain logistics based on rfid and epc," vol. 790, no. 1, 2020.

[32] Y. Sun and H. Wang, "Construction of third-party cold chain logistics platform based on radio frequency identification technology," vol. 452, no. 4, 2018.

[33] J. Ruiz-Rosero, G. Ramirez-Gonzalez, and J. Viveros-Delgado, "Software survey: ScientoPy, a scientometric tool for topics trend analysis in scientific publications," *Scientometrics*, vol. 121, no. 2, p. 1165 – 1188, 2019.

[34] T. Kelepouris, K. Pramatari, and G. Doukidis, "Rfid-enabled traceability in the food supply chain," *Industrial Management & data systems*, 2007.

[35] A. Abdelnour, F. Buchin, D. Kaddour, and S. Tedjini, "Improved traceability solution based on uhf rfid for cheese production sector," *IEEE Journal of Radio Frequency Identification*, vol. 2, no. 2, pp. 68–72, 2018.

[36] P. Liu, W. Liu, Q. Li, M. Duan, Y. Wang, and Y. Dai, "A research on tracing code of culture of food safety traceability based on rfid and improved epc," in *2016 International Conference on Logistics, Informatics and Service Sciences (LISS)*. IEEE, 2016, pp. 1–6.

[37] L. Cocco, K. Mannaro, R. Tonelli, L. Mariani, M. B. Lodi, A. Melis, M. Simone, and A. Fanti, "A blockchain-based traceability system in agri-food sme: Case study of a traditional bakery," *IEEE Access*, vol. 9, pp. 62 899–62 915, 2021.

[38] J. Ding, H. Xu, P. Li, and R. Xie, "Design and implementation of food safety traceability system based on rfid technology," in *Conference on Complex, Intelligent, and Software Intensive Systems*. Springer, 2017, pp. 657–666.

[39] T. Brown-Brandl *et al.*, "A review of passive radio frequency identification systems for animal monitoring in livestock facilities," *Applied Engineering in Agriculture*, vol. 35, no. 4, p. 579 – 591, 2019.

[40] H. Liu, "Logistic management in the supply chain market using bio-inspired models with iot assistance," *International Journal of Information Systems and Supply Chain Management (IJISSCM)*, vol. 15, no. 4, pp. 1–20, 2022.

[41] E. Bottani, M. Bertolini, A. Rizzi, and G. Romagnoli, "Monitoring on-shelf availability, out-of-stock and product freshness through rfid in the fresh food supply chain," *International Journal of RF Technologies*, vol. 8, no. 1-2, pp. 33–55, 2017.

[42] M. Conti, "Evo-nfc: Extra virgin olive oil traceability using nfc suitable for small-medium farms," *IEEE Access*, vol. 10, pp. 20 345–20 356, 2022.

[43] ——, "Food traceability in fruit and vegetables supply chain," in *2020 IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, 2020, pp. 1–5.

[44] B. B. Maskey, J. Sun, K. Shrestha, S. Kim, M. Park, Y. Kim, H. Park, S. Lee, Y. Han, J. Lee *et al.*, "A smart food label utilizing roll-to-roll gravure printed nfc antenna and thermistor to replace existing "use-by" date system," *IEEE Sensors Journal*, vol. 20, no. 4, pp. 2106–2116, 2019.

[45] D. Pigini and M. Conti, "Nfc-based traceability in the food chain," *Sustainability*, vol. 9, no. 10, p. 1910, 2017.

[46] D. Lenton, "From farm to fork [food supply chain tracking]," *Engineering & Technology*, vol. 5, no. 3, pp. 27–29, 2010.

[47] H. Ma, T. W. Brown, and A. T. Ho, "Uwb reactive near field detection for smart packages: a comprehensive study using eggs," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 7, pp. 3691–3701, 2017.

[48] I. Schumacher, J. Wöllenstein, and J. Kalbitzer, "Low-power uhf-rfid sensor tags for a complete monitoring and traceability of the cold chain," 2012.

[49] M. Yuan, R. Ghannam, P. Karadimas, and H. Heidari, "Flexible RFID patch for food spoilage monitoring," Oct. 2018, pp. 68–71.

[50] X. Xiao, B. Mu, and G. Cao, "Light-energy-harvested flexible wireless temperature-sensing patch for food cold storage," *ACS Applied Electronic Materials*, vol. 3, no. 7, pp. 3015–3022, 2021.

[51] P. Papetti, C. Costa, F. Antonucci, S. Figorilli, S. Solaini, and P. Menesatti, "A rfid web-based infotracing system for the artisanal italian cheese quality traceability," *Food Control*, vol. 27, no. 1, pp. 234–241, 2012.

[52] A. Eldebiky, M. Elsobky, H. Richter, and J. N. Burghartz, "Humidity and temperature sensor system demonstrator with nfc tag for hysif applications," *Advances in Radio Science*, vol. 16, no. D., pp. 109–116, 2018.

[53] K. Sima, T. Syrovy, S. Pretl, J. Freisleben, D. Cesek, and A. Hamacek, "Flexible smart tag for cold chain temperature monitoring," in *2017 40th International Spring Seminar on Electronics Technology (ISSE)*. IEEE, 2017, pp. 1–5.

[54] A. Pereira, E. Bergeret, O. Benzaim, J. Routin, O. Haon, L. Tournon, R. Coppard, and G. Depres, "Near-field communication tag development on a paper substrate—application to cold chain monitoring," *Flexible and Printed Electronics*, vol. 3, no. 1, p. 014003, 2018.

[55] F. Villa-Gonzalez, R. Bhattacharyya, T. Athauda, S. Sarma, and N. Karmakar, "Detecting breaks in cold chain integrity using chipless rfid time–temperature sensors," *IEEE Sensors Journal*, vol. 22, no. 18, pp. 17 808–17 818, 2022.

[56] H. Zhou, S. Li, S. Chen, Q. Zhang, W. Liu, and X. Guo, "Enabling low cost flexible smart packaging system with internet-of-things connectivity via flexible hybrid integration of silicon RFID chip and printed polymer sensors," *IEEE Sensors Journal*, vol. 20, no. 9, pp. 5004–5011, 2020.

[57] W. Wang, A. Sadeqi, H. R. Nejad, and S. Sonkusale, "Cost-effective wireless sensors for detection of package opening and tampering," *IEEE Access*, vol. 8, pp. 117 122–117 132, 2020.

[58] G. Khalil, R. Doss, and M. Chowdhury, "A comparison survey study on rfid based anti-counterfeiting systems," *Journal of Sensor and Actuator Networks*, vol. 8, no. 3, p. 37, 2019.

[59] W. Sun, X. Zhu, T. Zhou, Y. Su, and B. Mo, "Application of blockchain and rfid in anti-counterfeiting traceability of liquor," in *2019 IEEE 5th International Conference on Computer and Communications (ICCC)*. IEEE, 2019, pp. 1248–1251.

[60] P. Bernardi, F. Gandino, F. Lamberti, B. Montrucchio, M. Rebaudengo, and E. Sanchez, "An anti-counterfeit mechanism for the application layer in low-cost rfid devices," in *2008 4th European Conference on Circuits and Systems for Communications*. IEEE, 2008, pp. 227–231.

[61] K. Yang, U. Botero, H. Shen, D. L. Woodard, D. Forte, and M. M. Tehranipoor, "Ucr: An unclonable environmentally sensitive chipless rfid tag for protecting supply chain," *ACM Transactions on Design Automation of Electronic Systems*, vol. 23, no. 6, 2019.

[62] P. Olsen and M. Borit, "How to define traceability," *Trends in Food Science & Technology*, vol. 29, no. 2, pp. 142–150, 2013.

[63] G. Bianco, C. Occhiuzzi, N. Panunzio, and G. Marrocco, "A survey on radio frequency identification as a scalable technology to face pandemics," *IEEE J. Radio Frequency Identification*, vol. 6, pp. 77–96, 2022.

[64] C. Occhiuzzi, F. Camera, M. D'Orazio, N. D'Uva, S. Amendola, G. M. Bianco, C. Miozzi, L. Garavaglia, E. Martinelli, and G. Marrocco, "Automatic monitoring of fruit ripening rooms by uhf rfid sensor network and machine learning," *IEEE Journal of Radio Frequency Identification*, 2022.

[65] A. Abdelnour, N. Fonseca, A. Rennane, D. Kaddour, and S. Tedjini, "Design of rfid sensor tag for cheese quality monitoring," in *2019 IEEE MTT-S International Microwave Symposium (IMS)*. IEEE, 2019, pp. 290–292.

[66] C. Occhiuzzi, S. Caizzone, and G. Marrocco, "Passive uhf rfid antennas for sensing applications: Principles, methods, and classifcations," *IEEE Antennas and Propagation Magazine*, vol. 55, no. 6, pp. 14–34, 2013.

[67] B. Saggin *et al.*, "Food spoilage estimation using a sensing rfid tag," in *2022 3rd URSI Atlantic and Asia Pacific Radio Science Meeting (AT-AP-RASC)*, 2022, pp. 1–4.

[68] B. Saggin, Y. Belaizi, A. Vena, B. Sorli, V. Guillard, and I. Dedieu, "A flexible biopolymer based UHF RFID-sensor for food quality monitoring," 2019, pp. 484–487.

[69] R. Andre, Q. Ngo, L. Fugikawa-Santos, D. Correa, and T. Swager, "Wireless tags with hybrid nanomaterials for volatile amine detection," *ACS Sensors*, vol. 6, no. 6, pp. 2457–2464, 2021.

[70] S. Karuppuswami, S. Mondal, D. Kumar, and P. Chahal, "RFID coupled passive digital ammonia sensor for quality control of packaged food," *IEEE Sensors Journal*, vol. 20, no. 9, pp. 4679–4687, 2020.

[71] N. H. Nguyen, M. B. Lam, and W.-Y. Chung, "Battery-less pork freshness monitoring based on high-efficiency RF energy harvesting," *Journal of Sensor Science and Technology*, vol. 29, no. 5, pp. 293–302, 2020.

[72] Z. Ma, P. Chen, W. Cheng, K. Yan, L. Pan, Y. Shi, and G. Yu, "Highly sensitive, printable nanostructured conductive polymer wireless sensor for food spoilage detection," *Nano letters*, vol. 18, no. 7, pp. 4570–4575, 2018.

[73] S. Bhadra, D. J. Thomson, and G. E. Bridges, "Near field chipless tag for food quality monitoring," in *2014 16th International Symposium on*

Antenna Technology and Applied Electromagnetics (ANTEM). IEEE, 2014, pp. 1–2.

[74] T. Wu and S. Bhadra, "A printed LC resonator-based flexible RFID for remote potassium ion detection," *IEEE Journal on Flexible Electronics*, vol. 1, no. 1, pp. 47–57, 2021.

[75] X. Qian, Z. Li, Z. Meng, N. Gao, and Z. Zhang, "Flexible RFID tag for sensing the total minerals in drinking water via smartphone tapping," *IEEE Sensors Journal*, 2021.

[76] X. Xiao, B. Mu, G. Cao, Y. Yang, and M. Wang, "Flexible battery-free wireless electronic system for food monitoring," *Journal of Science: Advanced Materials and Devices*, vol. 7, no. 2, 2022.

[77] L. Zhang, H. Yang, Q. Tan, L. Jing, W. Zhang, J. Xiong, and P.-Y. Chen, "Wireless detection of biogenic amines using a split-ring resonator with silver nanoparticles-decorated molybdenum disulfide," *Sensors and Actuators B: Chemical*, vol. 343, p. 130155, 2021.

[78] R. Raju and G. E. Bridges, "A compact wireless passive harmonic sensor for ammonia sensing in packaged food," *IEEE Sensors Letters*, vol. 6, no. 4, pp. 1–4, 2022.

[79] ——, "Rcs based depolarizing passive tag with improved clutter rejection for potentiometric gas sensing," in *2019 IEEE SENSORS*. IEEE, 2019, pp. 1–4.

[80] T. Athauda, P. C. Banerjee, and N. C. Karmakar, "Microwave characterization of chitosan hydrogel and its use as a wireless ph sensor in smart packaging applications," *IEEE Sensors Journal*, vol. 20, no. 16, pp. 8990–8996, 2020.

[81] V. Mulloni, G. Marchi, L. Lorenzelli, and M. Donelli, "Chipless RFID sensing system for precise ethanol determination in alcoholic solutions," *Electronics*, vol. 11, no. 5, 2022.

[82] N. Javed, M. A. Azam, I. Qazi, Y. Amin, and H. Tenhunen, "Data-dense chipless rfid multisensor for aviculture industry," *IEEE Microwave and Wireless Components Letters*, vol. 30, no. 12, pp. 1193–1196, 2020.

[83] H.-D. Do, D.-E. Kim, M. Lam, and W.-Y. Chung, "Self-powered food assessment system using LSTM network and 915 MHz RF energy harvesting," *IEEE Access*, vol. 9, pp. 97 444–97 456, 2021.

[84] C. Occhiuzzi, N. D'Uva, S. Nappi, S. Amendola, C. Giallucca, V. Chiabrando, L. Garavaglia, G. Giacalone, and G. Marrocco, "Radio-frequency-identification-based intelligent packaging: Electromagnetic classification of tropical fruit ripening," *IEEE Antennas and Propagation Magazine*, vol. 62, no. 5, pp. 64–75, 2020.

[85] C. Occhiuzzi, F. Camera, N. D'Uva, S. Amendola, L. Garavaglia, and G. Marrocco, "Automatic monitoring of fruit ripening rooms by uhf rfid sensors and machine learning," in *2021 IEEE International Conference on RFID Technology and Applications (RFID-TA)*. IEEE, 2021, pp. 187–190.

[86] A. Sharif, T. Althobaiti, A. A. Alotaibi, N. Ramzan, M. A. Imran, and Q. H. Abbasi, "Inkjet-printed uhf rfid sticker for traceability and spoilage sensing of fruits," *IEEE Sensors Journal*, pp. 1–1, 2022.

[87] C. B. Hattab, S. Naoui, and L. Latrach, "Monitoring freshness of tommy mango fruit with an rfid tag," in *2022 Microwave Mediterranean Symposium (MMS)*. IEEE, 2022, pp. 1–6.

[88] X. Lv, Y. Zhang, Q. Shi, M. Temiz, and A. El-Makadema, "Examining food quality via rfid tag array," in *2021 International Conference on Microwave and Millimeter Wave Technology (ICMMT)*. IEEE, 2021, pp. 1–3.

[89] P. Escobedo, M. Bhattacharjee, F. Nikbakhtnasrabadi, and R. Dahiya, "Flexible strain sensor with NFC tag for food packaging," 2020.

[90] ——, "Flexible strain and temperature sensing NFC tag for smart food packaging applications," *IEEE Sensors Journal*, vol. 21, no. 23, pp. 26 406–26 414, 2021.

[91] T.-B. Nguyen, V.-T. Tran, and W.-Y. Chung, "Pressure measurement-based method for battery-free food monitoring powered by NFC energy harvesting," *Scientific Reports*, vol. 9, no. 1, 2019.

[92] R. Miscioscia, A. De Girolamo Del Mauro, E. Massera, A. Imparato, and C. Minarini, "Embedding a critical temperature indicator in a high-frequency passive RFID transponder," *IEEE Journal of Radio Frequency Identification*, vol. 4, no. 3, pp. 256–264, Sep. 2020.

[93] X. Xiao, Y. Fu, Y. Yang, M. A. Nikitina, and X. Zhang, "Battery-free wireless moisture sensor system for fruit monitoring," *Results in Engineering*, vol. 14, p. 100420, 2022.

[94] S. D. Hossain, M. A. P. Mora, A. Arif, B. Lohani, and R. C. Roberts, "Flexible chipless rfid temperature memory sensor," in *2022 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS)*. IEEE, 2022, pp. 1–4.

[95] A. Abdelnour, A. Rennane, D. Kaddour, and S. Tedjini, "Non-destructive dielectric characterization method for food products," in *2017 IEEE MTT-S International Microwave Symposium (IMS)*. IEEE, 2017, pp. 2022–2024.

[96] C. Macciò, M. Lodi, N. Curreli, L. Mariani, A. Melis, M. Simone, G. Muntoni, G. Mazzarella, M. Bozzi, and A. Fanti, "Preliminary design of a double ridge waveguide device for monitoring the complex permittivity of carasau bread doughs," in *2022 16th European Conference on Antennas and Propagation (EuCAP)*. IEEE, 2022, pp. 1–5.

[97] M. B. Lodi, N. Curreli, A. Melis, E. Garau, F. Fanari, A. Fedeli, A. Randazzo, G. Mazzarella, and A. Fanti, "Microwave characterization and modeling of the carasau bread doughs during leavening," *IEEE Access*, vol. 9, pp. 159 833–159 847, 2021.

[98] G. Muntoni, A. Fedeli, M. B. Lodi, M. Simone, A. Randazzo, G. Mazzarella, and A. Fanti, "Designing a microwave moisture content sensor for carasau bread: A feasibility study," in *2022 16th European Conference on Antennas and Propagation (EuCAP)*. IEEE, 2022, pp. 1–5.

[99] X. Zhang, C. Ruan, W. Wang, and Y. Cao, "Submersible high sensitivity microwave sensor for edible oil detection and quality analysis," *IEEE Sensors Journal*, vol. 21, no. 12, pp. 13 230–13 238, 2021.

[100] F. Galgano, F. Favati, M. Bonadio, V. Lorusso, and P. Romano, "Role of biogenic amines as index of freshness in beef meat packed with different biopolymeric materials," *Food Research International*, vol. 42, no. 8, pp. 1147–1152, 2009.

[101] C. Gomes, M. E. Castell-Perez, E. Chimbombi, F. Barros, D. Sun, J. Liu, H.-J. Sue, P. Sherman, P. Dunne, and A. O. Wright, "Effect of oxygen-absorbing packaging on the shelf life of a liquid-based component of military operational rations," *Journal of food science*, vol. 74, no. 4, pp. E167–E176, 2009.

[102] The university of Maine, "The Role of Ethylene in Fruit Ripening," Maine, United States of America. Accessed: 10 July 2022. [Online]. Available: https://extension.umaine.edu/fruit/harvest-and-storage-of-tree-fruits/the-role-of-ethylene-in-fruit-ripening/.

[103] Tamil Nadu Agricultural University - Agritech, "Fruit ripening," Coimbatore, India. Accessed: 10 July 2022. [Online]. Available: https://agritech.tnau.ac.in/horticulture/fruit_ripening.pdf.

[104] A. B. Barba, G. M. Bianco, L. Fiore, F. Arduini, G. Marrocco, and C. Occhiuzzi, "Design and manufacture of flexible epidermal NFC device for electrochemical sensing of sweat," in *2022 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS)*, Vienna, Austria, July 2022, pp. 1–4.

[105] C. Occhiuzzi, S. Amendola, S. Nappi, N. D'Uva, and G. Marrocco, "Rfid technology for industry 4.0: Architectures and challenges," in *2019 IEEE international conference on RFID technology and applications (RFID-TA)*. IEEE, 2019, pp. 181–186.

[106] A. H. F. Marques *et al.*, "Environmentally friendly, semi-transparent, screen printed antenna for rfid tag applications," *Brazilian Journal of Physics*, vol. 51, no. 3, pp. 434–438, 2021.

[107] J. Machiels, R. Appeltans, D. K. Bauer, E. Segers, Z. Henckens, W. Van Rompaey, D. Adons, R. Peeters, M. Geiβler, K. Kuehnoel *et al.*, "Screen printed antennas on fiber-based substrates for sustainable hf rfid assisted e-fulfilment smart packaging," *Materials*, vol. 14, no. 19, p. 5500, 2021.

[108] F. Villa-Gonzalez, R. Bhattacharyya, and S. Sarma, "Single and bulk identification of plastics in the recycling chain using chipless rfid tags," in *2021 IEEE International Conference on RFID (RFID)*. IEEE, 2021, pp. 1–8.

[109] D. Tellbach, F. Villa-Gonzalez, H. Li, R. Bhattacharyya, and S. Sarma, "Wireless Material Identification in the Recycling Chain Using Chipless RFID Tags," 6 2022. [Online]. Available: https://www.techrxiv.org/articles/preprint/Wireless_Material_Identification_in_the_Recycling_Chain_Using_Chipless_RFID_Tags/19962938

[110] X. Chen, H. He, L. Ukkonen, and J. Virkki, "3d-printed eco-friendly and cost-effective wireless platforms," in *2018 7th Electronic System-Integration Technology Conference (ESTC)*. IEEE, 2018, pp. 1–3.

[111] D. Gupta, D. Sood, M. Yu, and M. Kumar, "Compact biodegradable uhf rfid tag for short life cycle applications," pp. 399–401, 2021.

[112] M. Kumar, A. Sharma, and I. J. G. Zuazola, "A biodegradable multi-platform tolerant passive uhf rfid tag antenna for short-life iot applications," in *2021 IEEE Indian Conference on Antennas and Propagation (InCAP)*. IEEE, 2021, pp. 391–394.

[113] A. Mehmood, X. Chen, H. He, L. Ukkonen, and J. Virkki, "Eco-friendly flexible wireless platforms by 3d printing pen," in *2019 Photonics & Electromagnetics Research Symposium-Fall (PIERS-Fall)*. IEEE, 2019, pp. 2422–2425.

[114] A. Mehmood, X. Chen, H. He, S. Ma, L. Ukkonen, and J. Virkki, "Intelligent wristbands-fabrication of wearable rfid solutions by 3d printing pen," in *2020 IEEE International Symposium on Antennas*

and Propagation and North American Radio Science Meeting. IEEE, 2020, pp. 1319–1320.

[115] J. Morales-Guerra, F. Umaña-Idarraga, W. Giraldo-Escobar, E. Gonzalez-Valencia, and E. Reyes-Vera, "Performance analysis of a compact, flexible and biodegradable uhf rfid tag antenna," in *2021 International Conference on Electromagnetics in Advanced Applications (ICEAA)*. IEEE, 2021, pp. 357–360.

[116] Y. Sui, A. N. Radwan, A. Gopalakrishnan, K. Dikshit, C. J. Bruns, C. A. Zorman, and G. L. Whiting, "A reactive inkjet printing process for fabricating biodegradable conductive zinc structures," *Advanced Engineering Materials*, p. 2200529, 2022.

[117] M. Fantuzzi, D. Masotti, and A. Costanzo, "A novel integrated uwb–uhf one-port antenna for localization and energy harvesting," *IEEE Transactions on Antennas and Propagation*, vol. 63, no. 9, pp. 3839–3848, 2015.

[118] H. Rajagopalan and Y. Rahmat-Samii, "Novel ingestible capsule antenna designs for medical monitoring and diagnostics," 2010.

[119] H. Yu, C.-M. Tang, and R. Bashirullah, "An asymmetric RF tagging IC for ingestible medication compliance capsules," 2009, p. 101 – 104.

[120] H. Tao, M. A. Brenckle, M. Yang, J. Zhang, M. Liu, S. M. Siebert, R. D. Averitt, M. S. Mannoor, M. C. McAlpine, J. A. Rogers *et al.*, "Silk-based conformal, adhesive, edible food sensors," *Advanced Materials*, vol. 24, no. 8, pp. 1067–1072, 2012.

[121] S. Gopalakrishnan, J. Waimin, A. Zareei, S. Sedaghat, N. Raghunathan, A. Shakouri, and R. Rahimi, "A biodegradable chipless sensor for wireless subsoil health monitoring," *Scientific reports*, vol. 12, no. 1, pp. 1–14, 2022.

[122] Rfid suistanable tags. [Online]. Available: https://rfid.averydennison.com/en/home/products-solutions/rfid-sustainable-tags.html

[123] Identiv. (2022) Eco-friendly rfid and nfc tags. [Online]. Available: https://www.identiv.com/products/rfid-tags-inlays-labels/nfc/eco-friendly-rfid-nfc-tags

[124] Storaenso. (2020) Eco rfid passes industry tests for biodegradability. [Online]. Available: https://www.storaenso.com/en/newsroom/news/2020/4/eco-rfid-passes-industry-tests-for-biodegradability

[125] L. Roselli, *Green RFID systems*, 1st ed. Cambridge, England, UK: Cambridge University Press, 2014.

[126] A. S. Sharova, F. Melloni, G. Lanzani, C. J. Bettinger, and M. Caironi, "Edible electronics: The vision and the challenge," *Advanced Materials Technologies*, vol. 6, no. 2, 2021.

[127] S.-Y. Yang *et al.*, "Powering implantable and ingestible electronics," *Advanced Functional Materials*, vol. 31, no. 44, 2021.

[128] Y. Wu *et al.*, "Edible and nutritive electronics: Materials, fabrications, components, and applications," *Advanced Materials Technologies*, vol. 5, no. 10, 2020.

[129] J. Greene, *Degradation and Biodegradation Standards for Starch-Based and Other Polymeric Materials*, 2014.

[130] M.-R. Manel, A. Gupta, J. L. Rojo-Álvarez, and C. Christodolou, *Machine Learning Applications in Electromagnetics and Antenna Array Processing*. Norwood, MA, USA: Artech House, 2020.

[131] G. Alfian, M. Syafrudin, U. Farooq, M. R. Ma'arif, M. A. Syaekhoni, N. L. Fitriyani, J. Lee, and J. Rhee, "Improving efficiency of rfid-based traceability system for perishable food by utilizing iot sensors and machine learning model," *Food Control*, vol. 110, 2020.

[132] G. D. Cha, D. Kang, J. Lee, and D.-H. Kim, "Bioresorbable electronic implants: History, materials, fabrication, devices, and clinical applications," *Advanced Healthcare Materials*, vol. 8, no. 11, 2019.