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Edible Electronics: The Vision and the Challenge

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Many forward-looking biomedical, pharmaceutical, and food industry technologies have limited applications owing to the lack of crucial factors: balance of safety and reliability, cost-efficiency, and suitability for self-healthcare monitoring. The newly minted field of edible electronics, while at an embryonic stage, is creating great scientific resonance by envisioning a technology which is safe for ingestion, environmentally friendly, cost-effective, and degraded within the body after performing its function, either digested or even metabolized. Yet there is no shared approach, and the field is currently unified only by the use of food-derived or edible synthetic functional materials. In order to help shape the field more consistently, the main ideas and perspectives that have been proposed in the recent past are critically curated, underlining what edible electronics is and will be in the future according to the vision. Long-term opportunities in terms of environmentally friendly smart technologies, remote healthcare monitoring, and the formidable challenges ahead are discussed, covering major issues with respect to safety, materials approval, processing, power supply, communication, and human body interaction. A key point in moving toward such a vision is a strong interdisciplinary cooperation, which is highly encouraged.

1. Introduction

Science fiction embodies into futuristic technologies many fundamental human wishes and it can sometime foresee solutions that become later real applications. One example is the dream to look at our body from inside, and to intervene directly with precise and targeted actions to repair it, as we do on macroscopic machines. Indeed Asimov described this in his *Fantastic Voyage*, by dreaming of miniaturized men inside a miniature ship. This artistic view is far to be thinkable, let alone doable, but the idea to look at and act upon the body from inside is not. As a matter of fact, ingestible electronics is already a commercial technology. Here we describe how an alternative, safer, digestible or even metabolizable technology may as well become a reality and an opportunity for self-administered smart medications and food safety monitoring.

Quam multa fieri non posse priusquam sunt facta indicantur?
How many things are judged impossible before they actually occur?
Gaius Plinius Secundus /In Pliny: Natural History (1947), Vol. 2, Book 7, 511

1.1. Historical Background

1.1.1. From Ingestible to Edible

Edible electronics can be considered an evolution of the most traditional concept of ingestible electronics where the proposed devices, besides being suitable for swallowing, are fully digestible within the body, and safely releasable into the environment without need of recollection.

The concept of a telemetric ingestible device,[1,2] administered safely in pill shape, actually pairs with the ongoing care-provider effort spent in moving toward a more decentralized home-care system. Such action aims at lightening the hospital structures,[3] by shortening hospital stay, and reducing the number of recovery and readmissions, while increasing at the same time the number of interactions with the patient.[4] In this direction, telemedicine made great strides, enabling a long distance and continuous monitoring of patients parameters, exploiting a deep network made available by the emerging Internet of Things (IoT).[5]

Implantable and wearable electronics have been considered for long time the leading technologies within this framework, with their strengths and weaknesses. On the one side, there are implantable and highly performing tools working almost in contact with the region of interest, but characterized by costly and invasive implantation procedures and need for maintenance of the device. On the other, cheaper and much less invasive

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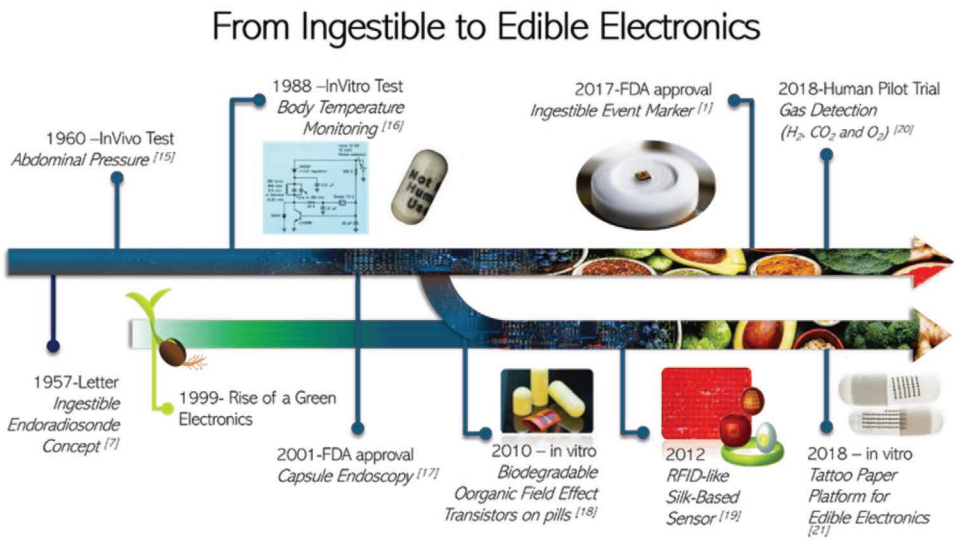

Figure 1. Pathway from the first visionary concept of ingestible endoradiosondes to versatile platforms for edible electronics. The timeline shows some of the most notable examples that represented milestones in the field progress. Rise of green electronics contributes to the detour toward edible electronics. The green and edible vision opened perspectives also on applications far from the biomedical field. 1957—Endoradiosonde concept for telemedicine.[7] 1960—First in vivo test for telemetric abdominal pressure monitoring.[15] 1988—In vitro test for a precise body temperature monitoring. Adapted with permission.[16] Copyright 1988, The Johns Hopkins University Applied Physics Laboratory. 2001—First FDA approval for an endoscopy capsule.[17] 2010—First concept of edible OFET, adapted with permission.[18] Copyright 2010, Wiley-VCH GmbH & Co. KGaA, Weinheim. 2012—Silk-based edible RF and THz resonators for food status monitoring. Adapted with permission.[19] Copyright 2012, Wiley-VCH GmbH & Co. KGaA, Weinheim. 2017—FDA approval of an ingestible event marker. Adapted with permission.[1] Copyright 2015, Elsevier Ltd. 2018—Human pilot trial for an ingestible gas sensor.[20] 2018—Tattoo paper platform for edible electronics applications. Adapted with permission.[21] Copyright 2018, Wiley-VCH GmbH & Co. KGaA, Weinheim.

systems that can be worn, but with a poor actuating and monitoring capability on organs far from the epidermal layers.[1]

Ingestible electronics places in between,[2,6] by exploiting semiinvasive medical devices for which a limited contact time with the body is foreseen, providing at the same time an efficient operation at the gastrointestinal (GI) level. The idea of ingestible electronics have to be sought back in the 1950s.[7] Early examples of ingestible electronics focused primarily on innovations in circuit design for sensing and telecommunication.[8] Materials selection criteria for ingestible devices were likely secondary considerations, as they were fixed by the only available technologies, starting from germanium transistors and only later moving to silicon. Packaging materials were therefore key to allow ingestion, often rarely more sophisticated than rigid impervious polymers, often polycarbonate.

We have to wait the beginning of the 21st century in order to have the first Food and Drugs Administration (FDA) approval for an ingestible camera[9,10] and 2017 for the approval of the first ingestible digital system able to dissolve within the body, apart from a small silicon chip, without the need of device recollection.[11] In the light of these steps forward, what was first a futuristic vision, is nowadays a concrete technology, with applications that stretch from drugs compliance[11,12] to the more electronically sophisticated video endoscopy.[13] Looking at current available ingestible devices, these are generally certified as inert and safely ingestible when considered as a whole system, although embedding poisonous and not disposable materials not in direct contact with body tissues; retention hazards have also to be taken in account for bulky systems.[14] All these properties lead to the need for device recollection and supervised administration, where patency tests before and a close contact with health providers during administration are often required. These constraints limit the most probable applications in a confined circle of pathologies where the benefits outweigh risks and costs.

Precisely for these limitations, it is evident the interest for an edible electronics development, exploiting disposable and harmless materials, easy and safe to digest. This progress has the potential to further unbalance the risk and benefit relation, extending the use of this technology on a larger selection of applications thanks to the possibility of an unsupervised administration, from diagnostic purposes in the "over the counter" medicine to the smart tagging of food industry products. Edible electronics can be identified as a novel concept that broadens the horizon of the more established ingestible electronics field and takes its roots from the ideas of green and biodegradable technologies, which exploit bioinspired and environmentally friendly materials as fundamental building blocks (**Figure 1**).

1.1.2. Edible Electronics: Arising from Green Technologies

The unconventional field of edible electronics takes inspiration from the previous interdisciplinary "green" approaches undertaken by the scientific community toward a safe and sustainable future. By 1970s green engineering gained momentum, promoting the idea of designing processes and products in a way that reduces impact on the environment and minimizes risks to human health.[22] Green chemistry has evolved within the same period: its major target was to scale down waste production across the life cycle of a chemical product, including its design, manufacture, use, and ultimate disposal.[23–25] That included curtailing or eliminating the use and generation of hazardous chemical feedstocks, reagents, and solvents. The 12 principles of green engineering and chemistry enable a sustainable path

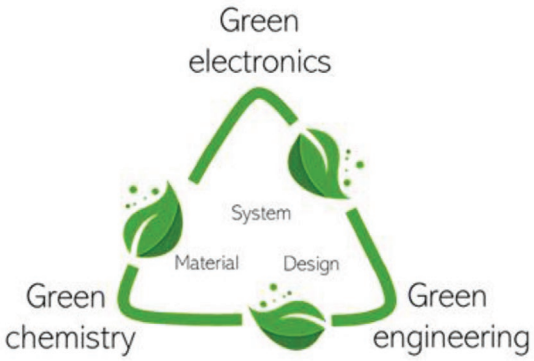

Figure 2. The "green triangle:" visual representation of the scientific and technical efforts shaping the "green" concept. Stages of the "green" fabrication cycle and disciplines responsible: design—green engineering; material—green chemistry; final system—green electronics.

when designing new materials, products, processes, and systems.[26–28] With the technological development and the expansion of consumption driven society, the problem of plastic and electronic waste (e-waste) became more urgent. Suggesting new alternatives to conventional plastics and polymers, the concept of biodegradable materials (emerged in the late 19th century with the discovery of the cellulose-based parkesine celluloid,[29,30] cellophane,[31] and casein-delivered galalith[32] bioplastics) started to gain momentum. Since the mid-1990s, e-waste has been recognized as the fastest-growing category of hazardous solid waste in the world with the current stream of 400 million tons per year.[33,34] Striving to reverse the prevailing destructive cycle, research targeting green electronics started to take the first steps.[35–39] Along with other "green" disciplines, green electronics took an inherent part of the formed "green triangle" (**Figure 2**), the components of which are interdependent and strongly connected one with another. Carrying forward the idea of nontoxic, human and environmentally friendly electronics, the proposed field has quickly drawn the attention of various research groups worldwide. Utilizing resources of a vast nature repository has become a central pillar of green electronics development. Active attempts are currently taken toward utilizing materials of natural origin, biodegradable, biocompatible (if applicable, considering one of the leading opinion papers[40]) and organic (carbon-based) for fabrication of various green electronic devices.[41–43]

Green-oriented research has been an important precursor to the development of edible electronics, explicitly introduced as a term in the manuscript by Bauer and co-workers in 2010.[18] Going past the traditional model of electronic devices, edible electronics envisions a technology which is not only environmentally friendly, cost-effective, energy-efficient, but also safe for ingestion, and degradable within the body after performing its function by either being digested or even metabolized. The ultimate goal of this new approach is to exploit the inherent electronic properties of food, food-derived or edible synthetic materials for development of ingestible functional electronic devices and systems.

1.2. Concept and Long-Term Vision

Having in mind the historical background discussed above, we highlight that even though edible electronics shares in some way the ideas of both green and ingestible electronics, it represents an independent field of research. By exploiting a rather ambitious approach, the adoption of edible materials as electronics constituent, edible electronics aims at the unique combination of electronic functionality and edibility to serve as a tool for disciplines targeting improvement of life quality. Besides fulfilling the key electronic duties of tracking, monitoring, sensing, and data transmission, the novel electronic devices composed of food and naturally derived materials, are intended to undergo degradation within the body after accomplishing their task.

We can foresee two categories of edible electronic systems that can be classified depending on the nature of the final implementation, specifically, systems operating from within the GI tract and those performing their function outside the body before being consumed. Whereas the first category keeps the focus mainly on biomedical and pharmaceutical applications, the second extends its influence to food industry (**Figure 3**).

Considering the importance of health status monitoring within the GI system, the introduced technology could target a significant number of critical biomedical tasks, with potential applications ranging from diagnostics and point-of-care testing to therapy and controlled drug delivery. For example, edible electronics devices can be adapted for rapid and precise detection of gastrointestinal bleeding[44,45] or diagnostics of steatorrhea through monitoring of fat acids in the lower GI tracts. A range of pathologies and disorders of the GI system can also be monitored by sensing the essential physical and chemical parameters of GI environment like pH,[46] temperature, or peristalsis.[47] Electronics with novel and unique capability of being safely ingested and metabolized can be consumed by patients on a daily base, along with pills or even food. Eliminating the need of device recollection and, consequently, hospitalization, data on the patients' health would be transmitted in real time to healthcare professionals. Edible electronics systems in form of a "smart pill" can fulfil the function of digital monitoring of medicine intake in the context of chronically treated conditions. In addition, edible electronics offers a strategy for targeted drug delivery providing control of the rate, time and place of drug release in the digestive system, thus representing a promising therapeutic tool.[48]

Sharing the ideas of the above-mentioned applications, pharmaceutical industry might as well benefit from edible electronics technology, in particular, when dealing with the category of the devices operating outside the body. In this context, identification (ID) "smart" edible electronics labels integrated with the medicine (pills) can represent a sensing solution against fraud and counterfeit pharmaceutical products or provide the control of the drugs exposure to the external conditions like UV, temperature, and humidity. The concept of edible electronics implies that the ID "smart" label can be consumed along with the medicine without the need to be removed before administration.

Once considering an inherently edible, harmless and environmentally friendly technology, applications far from the medicine field can also be addressed. Edible electronics can expand its applicability to the sector of food industry, where monitoring and tracking of quality of food (especially perishable one) along the distribution chain, are the primary objectives. Indeed, the increasingly stringent limits imposed by the authorities for

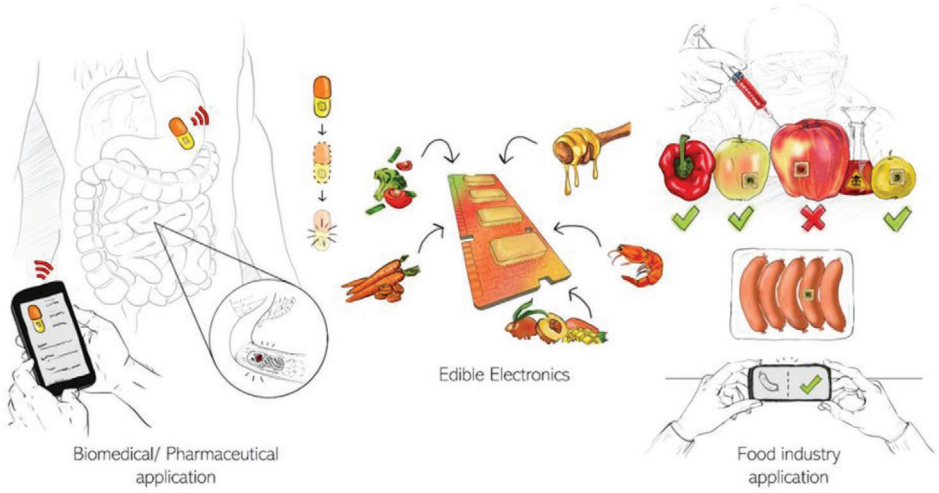

Figure 3. Concept and long-term vision applications of edible electronics. Edible electronic devices are composed entirely of food-based or edible synthetic materials derived from sustainable sources, and are intended to undergo degradation within the body, digested or metabolized, after accomplishing their task. Biomedical/pharmaceutical applications targeting diagnostics, therapy, and drug delivery are depicted (edible electronics is represented in the form of a smart pill that is digested/metabolized within the body). Food industry application: direct labeling of food without packaging thanks to edible "smart" tags communicating with the user in real time. "Smart" tags represent a tool for food quality monitoring, in particular perishable ones, along the distribution chain, and can serve as indicators of spoilage and contaminants (pesticides, antibiotics, bacteria, or biogenic amines).

acceptable quality and safety level require higher monitoring levels. In the light of this perspective, edible electronics envisions edible and cheap "smart" tags that are placed in direct contact with the food product and can be consumed with it, additionally eliminating the need of extra packaging. The introduction of such "smart" tags could improve the quality control in terms of traceability, contaminants and chemicals analysis, healthiness and safety regulation, leading at the same time to a reduction of food waste and limiting the use of polluting packaging with bulky and poorly informative labels.[49,50] Serving public health, edible electronics could control the state of the product and communicate its condition to the user in real time. The spectrum of monitoring systems is potentially wide ranging, from relatively simple and qualitative temperature–time indicators to sophisticated and quantitative sensors for detection of pesticides, antibiotics, bacteria, and biogenic amines.[51]

Within the framework of the discussed targeted applications, an edible electronic system represents a complex platform gathering all the essential electronic elements for the acquisition, elaboration and transmission of the data. The fundamental building blocks incorporate functional active/passive elements and circuits, sensors, power supplies, and communication strategies. In this context, discrete edible components such as diodes, resistors, capacitors, inductors, and transistors, are the key design elements for digital logic or frontend circuits for signal elaboration. Powering up of the system could be carried out by a galvanic cell that generates a potential in the stomach tract,[11] or by solid electrolyte batteries and supercapacitors built up with biopolymers and edible ions.[52] Simple passive radio frequency (RF) systems built up with certificated edible conductors[53] could also be used to power a simple circuit, either exploiting near field communication (NFC) or RF identification (RFID) protocols for the data transmission. Apart from RF, acoustic communication based on piezoelectric transducers is a possibility that edible electronics could utilize. Other signal transmission technologies can be employed to communicate information to the user, ranging from intrabody communication, which profits from the conductive property of the body, to simple optical visual feedbacks provided by electrochromic/thermochromic displays or light emitting devices adhered on shelf products.

Envisioning a cost-efficient and scalable technology producing sensitive, selective, robust, and completely safe devices at the same time is not straightforward, but mandatory for a technology that could become part of our daily life. Edible electronics, at the moment, appears a collection of isolated, non-coordinated attempts in different directions, unified only by the use of food-derived or edible synthetic functional materials. This unintelligibility does not help to identify consistent exploratory investigations and research directions, nor to clearly highlight the huge challenges that have to be tackled toward practical applications. In light of these obstacles, in order to shape the field in a more consistent manner, we collect here with a critical approach the main ideas, perspectives, and progress that have been achieved so far, underlining what edible electronics is and will be in the future according to our vision. The intention of this progress report is to contribute to create a converging vision of the scientific community on edible electronics and encourage, therefore, multidisciplinary cooperation moving toward such a big goal.

After providing a brief overview of the edible electronics concept and founding principles of this emerging field, we further take an inspirational step toward visualizing the path of edible electronics systems realization based on acquired knowledge. In the following section, we discuss the aspects of edible electronics materials and their selection criteria. Material regulating entities along with the protocols and standards adopted for the edibility and safety assessment are highlighted. We report a classification of notable edible materials on the basis

of their distinctive electronic properties and relevance as fundamental constituents (conductors: electronic and ionic; dielectrics, semiconductors). Next, we review frontline advances in the design and fabrication of edible electronics. Given that fully edible components and devices are currently rare, we cover notable examples of hybrid devices and systems, including also nonedible materials. This choice largely expands the number of concrete cases in which edible electronic materials have been successfully integrated and exploited, even in research not targeting edibility, demonstrating their potential and serving as an inspirational boost toward fully edible systems. Foreseeing the potential integration of edible electronics in our daily life, we examine the major principles of devices approbation regulations. Based on operational and functional capabilities, the subdivision of building electronic blocks onto functional micro- and opto-electronic components and circuits, sensors, power supplies and communication strategies, is introduced. Ultimately, we provide a perspective on future opportunities this new field can open, emphasizing the present challenges and pitfalls to consider.

2. Edible Materials: Ingredients for a Future Edible Electronics Platform

Our request here is clear and totally unconventional: we look for materials that combine useful electric properties, in order to be integrated into electronic devices, with biochemical and organoleptic properties that make them edible. The first compelling question is therefore: where do we find suitable edible candidate materials? Indeed, biodegradability and ingestibility are necessary, but not sufficient characteristics for edibility. Numerous green materials, despite their biodegradability (e.g., mater-bi, polyhydroxybutyrate, polyhydroxyalkanoate, among others) are inconvenient for human consumption. Regarding others used for implants and derived from natural and edible sources (e.g., polylactic acid, PLA, and poly(lactic-*co*-glycolic acid), PLGA, synthetized from starch fermentation) there is not yet evidence in support of their edibility, most likely because of a lack of interest in their ingestion so far. Moreover, inert compounds (polyethylene, Nitinol, stainless steel, polycarbonate, among others) used in gastrointestinal medical devices,[54,55] cannot be administered without a specific medical protocol and in any event be considered digestible.

The list of regulated and widely used edible materials for electronics purposes is broad: starting from abundant organic compounds as cellulose, chitin, activated carbon, and shellac up to metallic components as gold, silver, magnesium, and zinc, passing through dyes and natural pigments often proposed as semiconductive materials.[1,18] Even though these elements represent either the most abundant biopolymers in nature, e.g., cellulose or chitin, or fundamental nutrients for the human body, they had to go over an intense evaluation process by designated bodies able to verify their safety upon ingestion. Since biologically derived materials with minimal post processing are intrinsically advantageous for maximization of economic viability and minimization of environmental impact, the effort spent in this organization process goes beyond the edible electronics specificity.

The protocols and the standards adopted for the edibility and safety assessment of materials (or devices) are exhaustive but complex, especially if contextualized in an emerging and so far unclear context, as the one here discussed. First of all, a separation between food and drugs need to be introduced. Many are the substances accepted just for a pharmacological human administration, and then most likely suitable for a medical edible electronics with a diagnostic and therapeutic purpose. In a different context, limiting the inspection only to the use of "food" materials, a further classification between foodstuff and synthetic additive can be useful, by calling attention on the conservation protocols and on the maximum (and minimum) intake safety limits. This could bring to the market the first class of electronic devices equipped with a complete list of ingredients and a nutritional content table that stresses once more the interdisciplinarity of these studies. In this sense, we anticipate, and would like to promote, an important role played by food scientists in the shaping and development of this field.

It is important at this stage a clarification on the regulating organs role, focusing on the union between edible materials and electronics, and a broad literature review on edible functional materials, organizing the results obtained for each of the electronics fundamental constituents (conductors, dielectrics, semiconductors).

In this section, we introduce different classes of edible materials along with their characteristic electronic properties, focusing mainly on the potential such materials exhibit for development of edible electronics systems (**Figure 4**, **Table 1**). In addition, we carefully analyze the versatility of dielectric materials, also deepening their use as structural materials, in substrates, encapsulating layers, waveguides, and scaffolds. Moreover, by proposing minimum electrical properties requirements for each class of materials hereinafter, we establish target specifications needed for building a plausible edible electronics platform. In our view, this should serve as a seed from which a future database can be developed.

2.1. Materials Regulating Entities

While standards and protocols regulating the specific edible electronics niche do not exist, the organs coordinating the food and pharmacological industry are many and effective for many years now. Indeed, the US FDA is active from more than a century, with the aim of harmonizing and managing the public health, representing a landmark beyond the US borders as one of the most qualified organs for the safety assessment of food and drugs. Perhaps the most instructive guideline in choosing a material is selecting a candidate that is generally recognized as safe (GRAS). There are hundreds of GRAS materials catalogued by the US FDA including polymers, small molecules, and natural products. In particular, many of these materials are ideally suitable as substrates since they are dielectrics and can be processed into films and other useful form factors. Moreover, this agency shows a particular attention to the interaction of the human body with medical devices, showing also interest in the field of ingestible electronics, working on the approbation of several devices in the last decades.[9,11,13]

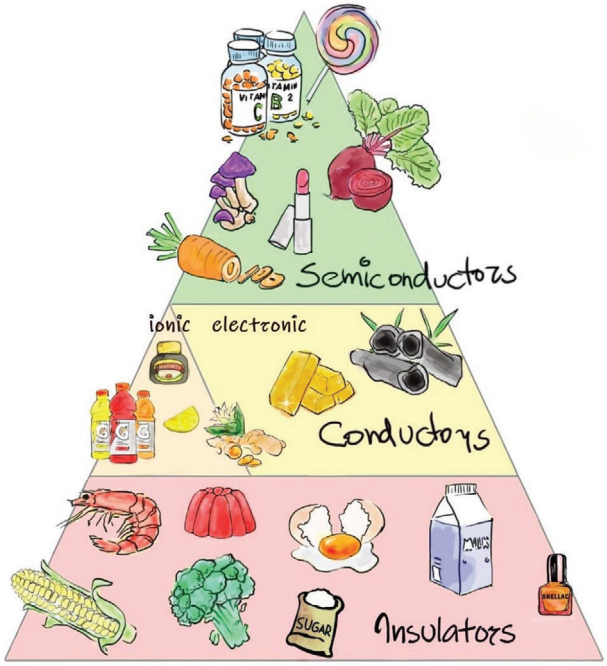

Figure 4. Foods, drugs, and vitamins, edible metals along with natural edible pigments, dyes, and polymers can be organized in a functional pyramid with respect to basic electrical properties: insulators, largely available, conductors, including ionic and electronic ones, and semiconductors, the most challenging materials to be developed in this framework, despite the large availability in nature of edible π-conjugated molecules. Insulators are in this illustration represented by corn starch, chitin, derived from shrimp shells, gelatin, dried broccoli, glucose, albumen, lactose, and shellac; conductors include edible gold, black carbon, lemon, Gatorade drink, and Vegemite/Marmite; semiconductors are represented by β-carotene pigment, abundant in carrots, perylene diimide, present in lipsticks, fungi-derived pigment xylindein, riboflavin (generally known as vitamin B2), indigo carmine food dye, and other pigments present in plants and food. The electrical properties available in literature for some of the visualized examples are listed in Table 1.

An evenly active, but more decentralized structure is settled in the European Union, where the European Food Safety Authority (EFSA) and the European Medicines Agency are dealing with safety and regulation of food and pharmaceutical products respectively.[56] They are regulatory entities providing standards, protocols and guidelines, but leaving the laws harmonization on medical device to an external directive.[57]

Both organs promote guidelines regulating nutritional requirements. The dietary reference value (DRV) from EFSA and the reference daily intake (RDI) from FDA define minimal and target values for a balanced and healthy diet. For some materials, where side effects were observed in case of chronic and/or abundant administrations, regulating entities settle an acceptable daily intake (ADI) limit, which should not be exceeded.

ADI becomes a fundamental variable in the edible electronics systems design, on par with a nutrition fact table on shelf-foodstuff. A recent work estimates the amount of semiconducting and conducting materials used in the fabrication of a single printable organic field-effect transistor (OFET), proposed for edible applications, to be in the order of few picograms and micrograms, respectively.[21] This evaluation forewarns the use of small quantities, reasonably under the ADI, also for more complex circuits. In this context, conductors and substrates remain the most critical elements, being generally the most abundant materials in the circuit.

Before a material can be accepted and added to the list of approved materials, with specific RDI or DRV, it is necessary to undergo a long path, passing through rigid protocols and tests that can last for years, often followed by long period of follow-up on a close number of users. Therefore, the complexity of the edibility assessment process and the immature nature of edible electronics has brought researchers to prevalently study the electronic properties of already approved materials, hardly ever taking the opposite approach (i.e., assessing toxicity of candidate edible electronic materials). However, this trend will have to be rebalanced in order to take the performances at a higher level.

It is therefore essential to comprehend the complexity of these agencies and their importance for edible electronics. Indeed, handling with an active and swallowable element equivalent to a typical drug or food and completely composed by GRAS materials, with specific DRV and a known ADI, strengthens the public acceptance of this technology compared to the administration of an ingestible foreign body.

2.2. Conductors

Conductors are essential components in electronic devices that appear in interconnections, electrodes, via throughs and more, depending on the intended function. Edible materials can naturally exhibit electronic or ionic conductivity, or the combination of both in many cases,[91–93] with ionic transport being a fundamental mechanism exploited in biology. In the following we review separately these two classes of edible conductors. With respect to that, we would like to highlight here the obvious importance of reporting the conditions at which conductivity is measured, and in particular whether it is a "quasi-static," DC measurement or an AC one. As a matter of fact, most typical electrodes used to test materials conductivity by applying a voltage and reading the corresponding current, would allow exchange of electrons and not of ions. To sustain DC ionic conductivity very specific electrodes would be required, such as Pd:H.[94] For this reason, DC conductivity is reported mostly for electronic conductors, while only AC conductivity can be accessed for ionic conductors in most cases. In the latter case, the specific frequency or range adopted should always be reported along with the conductivity value.

2.2.1. Electronic Conductors

The range of targeted DC conductivity values varies with the role of the conductor in the system. Interconnects/wires, power connections, and traces for inductors and antennas require relatively high, metallic conductivity, indicatively $>10^3$ S cm^{-1}. Electrodes for charge injection and collection enable device functionality at lower values. Low conductivity can also be favorable for passive components such as resistors.

Table 1. A toolkit of edible materials candidates classified with respect to their basic electrical property: electronic/ionic conductors, insulators, and semiconductors. Reference figures of merit and safe daily intakes are specified for each entry. Although the materials listed are GRAS, the guidelines for consumption are not reported for all of them. Where missing, the daily intake is marked as "not specified." Since the electronic performance of the material is highly dependent on the composition and processing conditions, here we report indicative ranges of values. μ_h: hole mobility, μ_e: electron mobility.

Electronic conductors	Conductivity [S cm^{-1}]	Daily intake	References
Gold [E175]	4.10×10^5	0.1–1.32 µg kg^{-1}	[58,59]
Silver [E174]	6.30×10^5	5–8.5 µg kg^{-1}	[58,60]
Activated carbon [E153]	0.001–1.940	0.5–1 g kg^{-1}	[61–63]
Magnesium	2.3×10^5	5.6 mg kg^{-1}	[64]
Zinc	1.69×10^5	40 mg	[65,66]
Copper	5.96×10^5	1.6 mg	[1,67]
Iron	1.00×10^5	8–45 mg	[68]
Calcium	2.98×10^5	2500 mg	[69]
Ionic conductors	**Conductivity [S cm^{-1}] (frequency range [Hz])**	**Daily intake**	**References**
Gatorade drink	$>2 \times 10^{-3}$ (0.01–10^5)	Not specified	[70]
Vegemite/Marmite	$20 \pm 3/13 \pm 1$ (frequency not specified)	Not specified	[71]
Hydrogel (gelatin powder + sodium alginate powder (E 401) + tap water) + NaCl	$(200 \pm 20) \times 10^{-3}$ (1–10^5)	Gelatin, not specified Na: 1.5–2.3 g Cl: 3.1 g	[72,73]
Chitosan + $NH_4CH_3CO_2$ (E264)	$(1.47 \pm 1.17) \times 10^{-4}$ (1–10^6)	Chitosan >0.05 g kg^{-1}[74] $NH_4CH_3CO_2$, not specified	[52,74]
Insulators	**Relative dielectric constant (frequency range [Hz])**	**Daily intake**	**References**
Cellulose (E 460 (i); E 460 (ii); E 461–466; E 468; E 469)	1.3–6 (100–1×10^6)	Not specified Suggested total daily exposure 660–900 mg kg^{-1}	[21,75,76]
Shellac (E904)	3–4 (50–500×10^3)	Not specified	[77,78]
Albumen	5–7 (100–1×10^6)	Not specified	[79,80]
Polyethylene oxide + I_2 (90/10 wt%) (E1521)	3–12 (1–50×10^3)	PEG: 5–10 mg kg^{-1} I_2: 600 µg per day	[81–83]
Powdered infant milk	1.6–3 (10×10^6–3×10^9)	Not specified	[84]
Glucose	6.35 (1×10^3)	Not specified	[85]
Aloe vera	3.39	Not specified	[86]
Starch	2.2–3.20 (2.2×10^9)	Not specified	[87]
Natural rubber	3.5–3.8 (≈5)	Not specified	[88]
Natural rubber + Sisal oil palm fibers	4–5 (≈5)	Not specified	[88]
Semiconductors	**Carrier mobility [cm^2 V^{-1} s^{-1}]**	**Daily intake**	**References**
β-Carotene	$\mu_h = 4 \times 10^{-4}$	5 mg kg^{-1}	[89]
Indigo	$\mu_{e,h} = 1 \times 10^{-2}$	5 mg kg^{-1} for indigo carmine	[90]
Perylene diimide	$\mu_e \leq 2 \times 10^{-2}$	8000 mg kg^{-1} in mice	[18]

The majority of natural and food derived materials exhibit very poor electronic conductivity, constraining their application as DC conductors for an edible electronics platform. However, a number of edible metals and minerals can be considered as potential candidates to fulfil that role due to their favorable electronic performance and significant level of RDI.

Within this concept, the most common and extensively utilized metal for fabrication of conductive components is gold

(Au). Gold with purity higher than 23 karat is a biologically inert stable substance that passes through the digestive tract without being absorbed. It is accepted in food industry as garnish to various food items, and is assigned with food additive code E175.[59] The substance in a form of gold leaf or processed through sputtering/thermal evaporation is widely exploited in different electronic devices, at the macro and microscale, targeting the concept of edibility.[19,58,70,95,96] Apart from gold, other noble metals like silver (recognized as bioinert food garnish) and platinum also excel in outstanding performance and potential to become a part of edible systems.[21,47,58,60,97] Yet, despite being nontoxic and benign, these compounds should be utilized with caution due to the possibility of accumulation in the GI tract under prolonged exposure/administration.[58,98] Particular attention should be also devoted to the control of the dimensions of the ingested object. Micro/nano sized insoluble residues are a potential hazard as, due to the large surface area, they interconnect with biological elements and may subsequently provoke toxic and adverse effects.[99,100]

Numerous promising edible conductive materials are listed in publications by Jiang and co-workers[96] and Bettinger,[1] who report RDI and specified functions of nontoxic metals and minerals employed in ingestible devices. Systems such as energy harvesters, ingestible and implantable sensors, and chemically powered ingestible micromotors have been successfully exploiting biodegradable Mg, Zn, Fe, and Cu-based materials in their design.[11,101–103]

Besides the above-mentioned edible electronically conductive compounds, non-metallic chemically stable carbon, in the form of activated charcoal, finds extensive application in edible food-based supercapacitors, electrochemical sensors and biofuel cells.[70,104–106] Activated charcoal and carbon black (CB) can be found in a wide variety of food and cosmetics products meeting European specifications with the marks E153 and E152, respectively. Performance of pure CB as a conductor is however limited by its low conductivity. Therefore, CB inks could be unsuitable when efficient conductive electrodes are mandatory, such as in the case of transistors. In order to optimize the functionality of CB, several approaches such as compression or incorporation of a variety of edible binders and biocatalysts in the CB matrix, have been explored.[70,104–107] Along with activated charcoal, other forms of carbon derived from processed foods, namely, carbonized sugar (cotton candy, $\sigma = 0.22$ S cm^{-1}), carbonized cellulose (cotton, $\sigma = 0.35$ S cm^{-1}), and carbonized protein (silk, $\sigma = 0.28$ S cm^{-1}), found practical implementation in resistors, inductors and antennas.[96]

An attractive approach related to the formation of another form of carbon, laser-induced graphene (LIG), has been demonstrated by the research group of Tour and co-workers. The study states that natural materials with high lignin content can be converted into conductive LIG by means of multiple pulsed laser scribing.[108] Porous LIG surfaces with ≤5 Ω sq^{-1} sheet resistance have been obtained on biodegradable substrates such as wood, paper, coconuts, potatoes, cardboard, and cloth. The authors suggest the application of LIG for edible electronics, for which a toxicity study would be required.

Throughout the family of edible conductors, biologically derived melanin pigments (responsible for the pigmentation degree of the human skin, hair, and eyes) have been discovered to sustain both electronic and ionic (specifically proton) currents.[93,109,110] A wide variety of melanin electrical conductivities has been reported ranging from 10^{-3} to 10^{-13} S cm^{-1} depending on the measurement conditions.[111,112] According to Pezzella and co-workers,[113] thermal annealing of the material in vacuum, resulting in structural reorganization of its molecular constituents, enabled to obtain unprecedented high conductivity values of eumelanin, up to 318 S cm^{-1}. As demonstrated in numerous studies, the conductivity of melanin is also hydration-dependent (approximately two orders of magnitude dry to wet).[114] Naturally occurring melanin pigments have been adopted as charge storage materials into supercapacitors and batteries.[3,93,97,109,110,115,116]

2.2.2. Ionic Conductors

There are many ionic conductors of natural origin that are of interest for edible electronics. Ionic conductivity represents a primary source of electrical conductivity in the natural world. To give an example, all types of biological systems use ion fluxes as an essential tool for signaling and communication.[117] Ionic compounds represent an indispensable part of iontronic,[118] (bio)sensing and energy storage devices, and can perform as the electrolyte-gating media for semiconductors or matrix for edible electrodes.

Ionic conductivity occurs due to the motion of anions and cations within the ion-solvating media. At the core of this phenomenon are electrolytic substances dissolved in a suitable solvent to give rise to mobile ions. Electrolytes come as acids, bases, salts, and even some biological doped polymers such as DNA[119] or polypeptides.

Liquid and solid electrolytes can be distinguished.[120] Despite the higher ionic mobility in liquid electrolytes with respect to solids, the implementation of the former in the operating device is limited by the unreliable liquid phase condition. In this case, solid state ionic conductors[121–124] potentially provide important advantages in terms of material stability and possibility of miniaturized fabrication down to the scale of thin films. Solid electrolytes are also appealing as they are solution processable, can be printed, and their sufficient robustness opens up opportunities for flexible and stretchable edible electronics. As an additional remark, in order to improve ionic conductivity of solid electrolytes, several approaches such as blending, plasticizing the electrolyte matrix, or incorporation of nano-sized fillers in the structure, have been employed.[125]

Electrolytic ionic conductors have been exploited in a number of edible electronics components and systems. Since mass flow in an electrolyte is subjected to complex frequency behavior, the frequency range of conductivity observation is an important parameter to be specified. Electrolytes in a form of hydrogels containing common NaCl salt have been introduced by in het Panhuis and co-workers[73] as a promising conducting material for edible electrodes (with conductivity of 200 ± 20 mS cm^{-1} characterized at frequencies between 1 and 10^5 Hz). Hydrogels are considered appealing building blocks for ingestible and implantable devices, as their compliant, biocompatible, and mechanical properties closely match the characteristics of biological systems. Other examples of food based gel-like

electrolytes are 3D printed Vegemite and Marmite breakfast spreads, which were found to exhibit DC conductivities of 20 ± 3 and 13 ± 1 S cm^{-1}, respectively, due to the presence of salt ions.[71] The use of electrolytes has been also demonstrated in the domain of edible energy storage devices such as batteries,[126] supercapacitors,[70,104] and fuel cells.[105] Furthermore, electrolytic materials constitute an important tool for sensing technologies that are of high interest for both food industry and biomedical applications.[127]

In addition to the above mentioned applications, edible electrolytes demonstrate potential as gating media in transistors. Electrolyte-gating of semiconductors provides favorable low-voltage operation of the device due to the high capacitance of the electrical double layer forming at the solid–electrolyte interfaces.[128] In this framework, pure/distilled water (self-ionized into hydronium and hydroxide ions) represents a common gating media for organic field-effect transistors (OFETs). Water-gated OFETs (WGOFETs) in the capacity of transducers in aqueous media open various opportunities for sensing applications.[129–131] Due to the simplicity of WGOFETs fabrication in relation to the conventional multilayered OFETs, they could also reveal a very helpful tool for rapid testing of new water-resistant edible organic semiconductor compounds. Edible electrolytic matrixes of chitosan, cellulose, agarose, and gelatin with dispersed salts have been also exploited within transistor architectures.[121,122,132,133] It is also important to acknowledge the relevance of electrolytes in electrochromic technologies.[134]

Electrolyte-based systems require the principal attention to operating conditions since most electrolytes are characterized by narrow electrochemical stability window. Moreover, the material performance can be dramatically affected by factors like the electrolyte evaporation and the ambient moisture uptake.[135]

For most of the edible electrolytes the common matrix medium is water. Many foods like vegetables and fruits are rich with electrolytes in a form of vitamins, minerals, and acids. An important remark to consider when dealing with edible materials is that fresh foods demonstrate very poor electrical conductivity as water is held immobile, trapped within the cells and the intercellular spaces within the structure of the material. However, once the cell membrane is broken by means of thermal heating, mechanical crushing, or enzymatic activity, the water containing charged ions is free to flow, producing an increase in conductivity.[136] The opposite effect of conductivity decrease occurs when fresh food undergoes dehydration.[96]

2.3. Dielectrics

Dielectric materials are fundamental and versatile building blocks for electronics in general. These elements are used both as constituent elements in substrates, insulating and encapsulating layers and for the active role that dielectric polarization plays in the operation of energy harvesters, resonating circuits and transistors.

They often represent the material embedded in the highest quantity in the final product. Such a large request needs a sustainable and cost-effective manufacturing. An opportunity in this direction is offered by some of the most abundant biopolymers in nature, such as cellulose and chitin, which show good mechanical and dielectric properties, in addition to being safe for ingestion over large ADI (if any).

As an alternative, it is possible to rely on a large variety of edible materials. The library of edible dielectrics is vast and among the categories here discussed, it is the widest. This multiplicity can be exploited to achieve a varied list of ingredients intra device, always keeping under control the intakes limits established by competent organs (e.g., World Health Organization, WHO, FDA, EFSA), lifting the standards toward a nutritive role of electronics. Most edible GRAS materials[137] are electrical insulators, which can therefore serve as dielectrics or encapsulation materials. Using GRAS materials as passive structural elements such as substrates, or as functional elements such as dielectric for electronics, offers important advantages. First and foremost, the toxicity profiles are well characterized and pose essentially negligible risks to the prospective user. There are several polymers that are GRAS that could potentially be used. Examples include gelatin, shellac, cellulose, dextrose, alginate, polyvinyl alcohol (PVA), gellan gum, and polyethyleneglycol (PEG).[77,138–143] One possible challenge with this approach is that many of these materials are often designed to preserve and protect food products. As such, some food-grade materials are not optimized or even compatible with many types of microelectronics manufacturing processes. Another important challenge is that many polymers that are GRAS are hygroscopic, posing additional challenges to the manufacturing and packaging of moisture sensitive components.

Among all the potential applications, dielectric materials found a large use as substrates, which are passive albeit necessary structural components. However, recent advances in materials and processes for manufacturing flexible and biodegradable electronics can enable next-generation strategies for designing substrate materials for edible electronics,[144] supporting and protecting the circuitry, while tuning its degradability, flexibility, thermal resistance, and stretchability.

The selection process for structural materials, active components, and packaging is application specific and depends on the intended function of the device within the gut. Choosing the appropriate substrate materials is no different. The substrate material is often, by definition, a passive structure that physically co-locates the components and provides structural integrity to devices. To that end, the ideal substrate should accomplish this goal using the smallest areal footprint while also minimizing the risk of adverse events to the patient. One such strategy is to use the ingested item, as pills, tablets or even food itself, as the substrate material. This vision is enabled by advanced in manufacturing of soft electronic materials and transfer printing techniques.[21]

In the context of edible electronic devices, the substrate is among the most abundant ingredients and it correlates with the device bulkiness. For this reason, it has a key role in sizing the risks related to adverse effects such as acute toxicity and device retention. These risks can be mitigated by designing substrates that in addition to be safe for ingestion are also mechanically flexible, or biodegradable.

Using flexible materials offer unique advantages in the design of edible electronic devices. First, devices with flexible substrates can be packaged into temporary ingestible form

factors. According to FDA specifications, the characteristic size of an ingestible device in a form of capsule or tablet should not exceed 22 mm at its largest dimension.[145] Electronic devices could be fabricated on substrates with larger characteristic dimensions. Doing so could aid in the design of sensing elements, antennas, or other device paradigms that benefit from large planar arrays of components.[146] Second, electronic devices fabricated on flexible substrates can mitigate one of the most important risks to the patient—device retention.[147] The risk of device retention for any ingestible device is proportional to the size of the smallest dimension.[145,148,149] Ingestible devices composed of deformable materials such as elastomers can more easily transit the constrictions in the GI tract compared to structurally rigid counterparts, thus reducing the risk of device retention. Electronic devices with high flexural rigidity can be achieved by using elastomeric substrates with ultra-thin membranes of functional electronic materials that may be large modulus materials.[150] For example, natural rubber has been successfully proposed as substrate for stretchable sensors.[151] Poly(dimethylsiloxane) (PDMS) silicone, on the other hand, is widely used in flexible electronics and medical devices, and in its pure form, without cross-linker agent, is employed as a food additive (E900). Silicones in particular are logical candidates for use as flexible substrate materials for edible electronic devices. They offer many advantages as a substrate material including tunable properties, low toxicity in various contexts, a rich history of use in medical devices, and established manufacturing practices. However, silicones are non-degradable and therefore pose a risk of accumulation in the gut.

Biodegradable substrates, on the other hand, are compelling because they can provide the necessary function of the device while obviating much of the risk of edible devices. There are numerous examples of biodegradable polymers for potential use as substrates in edible electronic devices including silk fibroin,[152] pea protein and apple extract,[144] caramelized sugar,[153] poly([alpha]-hydroxy acids) (e.g., poly(L-lactide), poly(glycolide), and their copolymers PLGA), and poly([epsilon]-caprolactones) (PCL). Some of these materials have been previously used as substrates in biodegradable electronic devices.[19,154] However, the most compelling class of substrate materials for edible electronic devices are those elastomeric, biodegradable, and comprised of simple metabolizable monomers.[155] Various classes of biodegradable elastomers have been synthesized and characterized in recent years, as poly(xylitol-*co*-citrate) obtained from the polycondensation of the FDA approved xylitol with water soluble citric acid.[156,157] However, a relatively small proportion have been used in edible electronic devices to date, e.g., glycerol, sebacic acid and cinnamon acid have been combined for the fabrication of an elastic and biodegradable substrate for edible batteries.[107] Novel biodegradable elastomers will likely enable new device concepts as interest in edible electronic devices continues to grow.

Apart from being used as structural materials, dielectrics are integrated in electronic components as functional elements. Selection of the right dielectric material for electronics applications includes different considerations compared to those for substrates. Beyond mechanical characteristics, as flexibility and degradability, it is necessary to concentrate on the material electrical properties such as its dielectric relative constant (ε_r) and its performance over a wide frequency range, other than its processability in pinholes free thin films, with good adhesion.

Silicon dioxide is among the gold standards for dielectric layers in complementary metal-oxide-semiconductors (CMOS) manufacturing, with ε_r ranging between 3.7 and 3.9 and exhibiting a good stability under high electric fields (dielectric strength of 10^7 V cm^{-1}). Moreover it is used in food industry as anticaking agent (E551) in its powder form. These characteristics make it a candidate as edible dielectric layer, if suitable processes are adopted. Rogers and co-workers have proposed a thermally grown silicon dioxide layer for transient implantable sensors, but application in edible devices has not been considered yet.[158]

A considerable contribution to alternative dielectrics characterization comes from the green technology concept, where the ambition of a sustainable and biodegradable electronics led to the integration of novel materials in various electronic devices. For example, in a 2010 work, Bauer and co-workers[18] demonstrated the possibility to use a wide range of edible materials (adenine, glucose, lactose, caffeine), with ε_r between 3 and 7, as gate dielectrics in OFETs operating at low voltage (around 5 V). Moving away from the electronic area, other fields allowed extending the edible insulators library. The biotechnology field, for example, deeply studied the dielectric properties of cells, DNA and several proteins classes, in order to better manipulate them with di- or electrophoresis techniques.[159,160] Moreover, food science from the 20th century deals with the characterization of the dielectric properties of foodstuff under the application of microwave electromagnetic field, with applications ranging from cooking to sterilization.[161,162]

One of the most common and used edible dielectric materials is cellulose, in all its forms. Currently EFSA classified ten different cellulose compounds as food additives (E460–E469), many of which already proposed multiple times as substrates and insulating layers,[21,163] or as dielectric scaffolds for smart materials[164] and ion conductive gels.[165] Cellulose nanocrystals have been successfully integrated in flexible OFETs as gate dielectric, showing $\varepsilon_r \approx 6$ in the 100 Hz-10 kHz frequency range.[166] In this specific work, nanocrystals have been deposited through drop casting from aqueous solution obtaining flexible films with a thickness of ≈140 nm. Lamination was also used to deposit ethylene cellulose films for the same purpose, achieving an areal capacitance between 4 and 5.5 nF cm^{-2} in a frequency range between 100 Hz and 10 MHz for a 100 nm thick film.[21] The adoption of this polysaccharide in electronics as dielectric and substrate layer (also simultaneously[167]), was broadly studied, leading to establishment of the term "paper electronics."[75]

Other exotic materials proposed as dielectric layers and commonly present in a human everyday diet are for example chicken albumen,[80] with ε_r between 5 and 6 (stable in the 200 Hz–1 MHz frequency range), and glucose, with $\varepsilon_r = 6.35$ measured at 1 kHz, both successfully integrated as gate dielectrics in OFETs.[18] Moreover, recently the dielectric and processability properties of wheat gluten and banana fibers were tested (ε_r between 2 and 6 in a frequency range from 100 Hz to 10 MHz).[168]

Moving back to structural properties, dielectrics are often used also as encapsulating layers in order to control the oxygen and water permeability, which becomes a critical point in the

perspective of devices sensitive to such agents. Examples are represented by beeswax and shellac composites,[169,170] both natural secretions of insects, whose barrier properties are strongly composition-dependent. In this respect, edible food packaging is an active research field within the framework of sustainable packaging.[171]

Although it may appear far from edible electronics related applications, dielectric materials as cellulose and silk were exploited for the fabrication of edible optical fibers[172] and waveguides,[173] representing a good path for transferring light through the GI tract, opening opportunities toward imaging, and monitoring based on edible systems.

In addition, some edible insulators were proposed as matrices in solid electrolytes[123,124,174] (PEG[E1521], chitosan, starch, among others), as biodegradable scaffolds for controlled drug release[175,176] or short term operation inside the GI system[177] and as smart structures able to self-orient at the stomach level.[178]

Moreover dielectric materials has been often proposed as biodegradable fillers able to tune the degradability of the device[179] or as a strategy to dilute materials with low ADI while keeping their function.

2.4. Semiconductors

Semiconductors are key to electronic functionalities, as they determine the operation of active devices, such as charge transport, light emission and photon to charge conversion. This is however the least investigated class of materials toward edibility. Examples of adoption of edible semiconductors in devices are indeed very scarce, and only few potential candidates have been proposed by the scientific community. This may appear surprising, since most chromophores in nature, and specifically in food, owe they color to the π-electron delocalization within their molecular structure. This bestows, in the solid state, many semiconducting properties that are at the basis of organic electronics. Yet, decades of organic semiconductors development, aimed at understanding structure–property relationships,[180–182] showed that efficient electronic properties in the solid-state depend critically on the molecular packing. This is particularly true for charge transport, which depends on the intermolecular coupling in the solid-state films. Apart from notable cases,[181,183,184] finding equivalent structures in nature is not trivial. Moreover, in contrast to conventional materials, the central pillar for edible semiconductors is not only high electronic performance, but also a challenging balance between inherent safety for ingestion and sufficient electronic stability to perform a specific function over a limited period of time.

In this context, materials of natural origin (e.g., DNA, proteins, pigments, and dyes) are of high interest since they feature strong intra and intermolecular hydrogen bonding that promotes intermolecular π-conjugated networks, providing stability in air and efficient charge transport.[185–188] To date, the majority of potentially edible semiconductors are constituted by pigments and dyes that are naturally derived from animals, foods, plants and minerals, or FDA approved artificially synthesized materials.[27–29,35,103–106] We emphasize the fact that, even though a number of promising semiconductors are synthesized starting from edible moieties, they cannot be considered edible *per se*, and require additional toxicological analysis.

Since toxicity depends on quantity, an effective strategy toward accessing edibility comes from biodegradable electronics,[179] and it consists in the reduction of the quantity of the active compound, for example, by blending it in an edible nontoxic matrix.

The most notable edible semiconductors that are recognized as safe and are approved as colorants/additives in cosmetics, drugs or foods are reviewed herein.[191] Since the majority of the reported cases is represented by insoluble pigments, vacuum-based thermal evaporation has been employed as a primary technique for the active layer deposition.

The most often recurring semiconductor in green and biodegradable electronics reports is indigo pigment, naturally extracted from flowering *Indigofera tinctoria* plants.[192–194] Indigo, along with its derivatives (e.g., cibalackrot), demonstrates ambipolar behavior in organic field effect transistors with balanced electron μ_e and hole μ_h mobilities in the order of 10^{-2} cm^2 V^{-1} s^{-1}. While indigo has not been officially recognized as edible, one soluble sulfate salt of it, indigo carmine, is the approved food colorant E132. Indigo carmine found application as a pH indicator in the 11.5–14 range, changing from blue to yellow, as a contrast agent for GI chromoendoscopy, and as a positive-electrode material for rechargeable sodium batteries.[195,196] Electronic properties[197] of this material as a semiconductor have been investigated, and its implementation in a photodiode[198] architecture has been demonstrated. Due to the edibility, solution-processability, and versatility of indigo carmine, further studies on its charge transport and mobility appear to be of a great interest. Tyrian purple, a dibromo derivative of indigo, is another pigment of natural origin obtained from Muricidae sea snails. This marine metabolite demonstrates efficient ambipolar transport, with balanced charge carriers field-effect mobilities around 0.3–0.4 cm^2 V^{-1} s^{-1}, competing with synthetic organic semiconductors.[194] A survey on the suitability of this material for ingestion did not produce any result. Biomaterial riboflavin tetrabutyrate (RFLT), the derivative of riboflavin (generally known as vitamin B2), has been successfully utilized in a solution-processed bio-organic light-emitting diode (OLED) by the group of Hernandez-Sosa.[199] RFLT revealed itself as a poor electron and hole conductor with conductivities of 2×10^{-11} S cm^{-1}.

Indanthrene yellow G (vat yellow 1) and indanthrene brilliant orange RF (vat orange 3), used as colorants for sausage skin in food industry,[200] are two examples of good electron transporting semiconductors derived from the natural anthraquinone compound, present in some plants, vegetables, and herbs.[18,201] These biodegradable materials demonstrate field-effect electron mobilities of 1.2×10^{-2} and 1.8×10^{-3} cm^2 V^{-1} s^{-1}, respectively. Another synthetic organic compound reported as a good electron transporting semiconductor is perylene diimide (PDI, Red Dye 190 or Lumogen F),[18,202] adopted to realize n-type OFETs (μ = 0.01–0.02 cm^2 V^{-1} s^{-1}). Pyrene-terminal functionalized PDI has been employed as an acceptor in bulk heterojunction solar cells (power conversion efficiency of 1.35% under the illumination of AM 1.5G, 100 mW cm^2).[203] Its toxicity is lower than that of table salt, and it is widely accepted for application in lipsticks, nail polishes, and hair dyes.[204] Fungi-derived

pigment xylindein, secreted from the *Chlorociboria aeruginosa*, has been recently investigated as a semiconductor for sustainable (opto)electronic applications. Exhibiting high photostability and space-charge-limited current effective electron mobility up to 0.4 $cm^2\ V^{-1}\ s^{-1}$, xylindein appears to be a promising candidate material for edible electronics.[205]

The class of potential hole transporting "edible" materials is represented in literature mostly by carotenoids, quinacridone, and phthalocyanines. Carotenoids, such as β-carotene, are linear π-conjugated molecules responsible for the bright yellow, red, and orange colors in plants, fruits, and vegetables (carrots, in particular). Officially recognized as a food coloring E160a, β-carotene, belonging to the group of carotenoids, exhibits poor charge carrier field-effect mobility of $4 \times 10^{-4}\ cm^2\ V^{-1}\ s^{-1}$.[18,89,206,207] One of the most prominent, low-cost synthetic hydrogen-bonded pigments, explored as an active material for solar cells and thin-film transistors, is quinacridone.[38] Quinacridone, known as a compound for printing inks, is also an FDA approved colorant for food-contact and some cosmetic products.[208] Achieving field-effect hole mobility of 0.1 $cm^2\ V^{-1}\ s^{-1}$, this pigment is characterized by excellent stability in OFETs operated in ambient air without encapsulation.[209] Functional phthalocyanines comprise another group of molecules widely studied as organic semiconductors.[210] In particular, copper phthalocyanine, classified as the cosmetic blue pigment CI 74160 and present in a variety of toothpastes, has shown hole transporting properties ($1.2 \times 10^{-3}\ cm^2\ V^{-1}\ s^{-1}$) in low voltage WGOFETs.[130]

Among candidate semiconductors for designing digestible electronics, silicon deserves to be mentioned. Crystalline, bulk silicon has great electronic properties, while silicon traces are present in the body. The edibility of bulk silicon along with its suitability for biointegration are still under debate,[211,212] but recent studies explore, as an alternative, amorphous and polycrystalline silicon in the form of nanomembranes (Si NMs). Due to the unique flexibility, low-cost potential, and solution processability of Si NMs, a variety of functional electronic devices, mostly for implantable devices, have been proposed.[213] Even though evidence of Si NMs edibility has not been obtained yet, the demonstrated outstanding biocompatibility and bioresorbability of the material,[214,215] in particular, doped with nutritive boron or phosphorus (tolerable intakes of ≈10 and 3000 mg per day respectively[216]), provides a strong ground for further investigation.

3. From Edible Electronic Components/Devices to Systems

Edible electronics aspires to develop fully edible electronic systems, performing multiple functions. However, owing to the severe challenges already at the single component level, examples of edible systems are very rare.

Ingestible electronics remains a great source of inspiration, with innovative diagnosis tools, as e-pills for real time endoscopy,[13,217] simple systems for compliance assessment[11] or pH and peristaltic movement sensors[46,47] for the GI tract monitoring in general.[2] Anyway, rarely they exploit edible materials, except for a few parts such as biodegradable scaffolds for drug delivery systems or inert coatings. As previously indicated, an important stimulus for functional materials comes from the green electronics field, which however does not aim at edibility. For this reason, examples of electronics device integrating biodegradable materials harmless for the environment, but not certificated for a safe ingestion, are more common in literature. As a matter of fact, a complex and autonomous edible system powered by an edible power supply, recording a selected parameter, elaborated by an integrated circuit and transmitted by an eatable communication system, does not exist yet. Anyway, recently, more and more are the valuable examples of devices that, voluntary or accidentally, can be grouped within the edible area.

The aim of this section is to describe the most representative edible devices and reports moving toward fully edible electronics, trying to group and coordinate all the efforts that are coming from the biomedical, food science, and sustainable engineering fields. Moreover, being edible electronics a novel and not well defined field yet, basic information and considerations on systems and medical devices approbation are presented.

With the duty of clarifying the current ongoing efforts, all the main fundamental modules composing electronics system are discussed. All the building blocks are well represented by multiple examples of edible or partially edible devices, comprising passive and active elements composing the circuits and aimed at sensing, as well as technologies exploited for providing power and the strategies for signal communication. Along with fully edible electronic components, we review here relevant examples where practical use of edible electronic materials is demonstrated in elements comprising also nonedible materials, as these represent a fertile ground for further edible electronics breakthroughs.

3.1. Systems Approbation

Edible electronics stands in between two distant fields. It imposes, from one side, to examine the device components as food (or drug) suitable for the human administration, with the previously mentioned constraints, while on the other hand, as an electronic device that necessitates all the certifications imposed by competent organs. Therefore, edibility is not a sufficient condition that allows automatically a faster path through market certifications, and if designed for diagnosis and treatment tools the directive for medical devices operation must be followed.

Two of the most important organs dealing with the medical devices safety regulations are FDA and the European Union with the "Regulation (EU) 2017/745 on medical devices"[57] that act promulgating regulations and guidelines to be observed for commercialization of products. These organizations provide a precise device classification that allows identifying the risks at which the patient is subjected during the medical system operation, and consequently providing appropriate safety protocols. Both FDA and EU-entity take advantage from a similar three classes system, from I to III, which with some differences passes from harmless passive devices designed for wearable external use, to invasively implanted devices potentially dangerous for the patient life, with requirements in terms of approbation and handling protocols becoming the more stringent, the higher the class is.[218,219]

It is worth mentioning that approbation of a system composed of edible components is not obvious. Definition of edible electronics implies the occurrence of device ingestion, transferring it inside the GI tract. This event could force both FDA and EU regulation to consider edible electronics systems as semi-invasive medical devices operating inside the body (class II or higher), also the ones meant to operate out of the body, which in the standard electronics context are often defined as class I. Moreover, edible devices embedding animal tissues or their derivatives also represent another characteristic example: despite their edibility should guarantee against toxicity and retention problems, they could be classified by the rule 18 of the EU lex automatically as a class III device,[57] the one with the highest risk. Therefore, edibility of used materials *per se* does not guarantee a simplified approbation process for the device. The authority organs are extremely precise and in constant optimization, but for obvious reasons have not yet regulated the field, because of its novelty and lack in benchmark. A model that has set a precedent is Abilify MyCite[11] from Proteus, the first ingestible medication system approved by FDA. It represents, to the best of our knowledge, the first example of an ingestible sensor also approved as a drug,[220] despite embedding components commonly not considered as edible (e.g., CMOS circuits).[221]

3.2. Micro and Optoelectronic Building Blocks

An essential principle of building an edible electronic platform is to envision separate functional electronic elements enabling the targeted final system. Depending on the nature of the function to be fulfilled, fundamental electronic building blocks are classified into passive and active ones.

Passive components such as resistors, inductors, and capacitors are ubiquitous in electronic design. Examples of edible passive components made out of food-based nutritive materials have been proposed by Jiang and co-workers.[96] The authors realized edible resistors and inductors utilizing sweet potato starch and carbonized cotton candy, and capacitors from gelatin and edible gold. The characteristic values of resistance, inductance, and capacitance achieved are in the order of kΩ, mH, nF, respectively. Le Borgne et al.[222] have demonstrated easily customizable inkjet-printed CB resistors on both PET and paper substrates. Due to the variable flat to bent resistance (11.7 to 59 kΩ), such CB-based passive components may find application as strain sensors. Moving toward "Do-It-Yourself" electronics, the same group proposed to combine the inkjet printing of the carbon ink with the screen printing of egg white (albumen) in order to fabricate edible capacitors.

In the following, active devices and circuits comprised of edible or integrating edible materials are reviewed.

3.2.1. Field-Effect Transistors

Transistors are key components in any circuit and are also a testbed for electronic properties of semiconductors, in particular, charge carrier transport. Among these, thin film field-effect transistors are among the mostly studied architecture in large-area and flexible electronics, and are therefore one of the most obvious options also for edible transistors.

Significant contribution to the sector of edible FETs has been made by Siegfried Bauer and collaborators, who reported the first potentially edible FET configurations exploiting various nature-derived and commodity materials, ranging from food to edible metals. The biodegradable, bioresorbable, and, in perspective, metabolizable transistors they demonstrated showed the possibility to achieve attractive electronic properties, such as an operational voltage as low as 4 V and a current on-off ratio up to five orders of magnitude.[18,85,194,223] Entirely or partially edible FETs of different designs built on edible hard gelatin capsules, Ecoflex, caramelized glucose and shellac (**Figure 5**a–d) showed saturated field effect mobilities in the range from 1.5×10^{-4} to 2×10^{-2} cm^2 V^{-1} s^{-1}. The best performances in terms of mobility reported so far for potentially edible FETs, according to our knowledge, have been achieved in n-type devices based on vat yellow 1 (μ = 0.012–0.015 cm^2 V^{-1} s^{-1}) and perylene diimide (μ = 0.01–0.02 cm^2 V^{-1} s^{-1})[18] and ambipolar devices based on indigo and tyrian purple (0.01–0.40 cm^2 V^{-1} s^{-1} for both carriers).[192]

There are few other groups that contributed to develop interesting approaches to edible or partially edible FETs. Bettinger and Bao investigated materials and fabrication strategies for the realization of organic p-type thin film transistors (Figure 5e) based on the small molecule semiconductor 5,5′-bis-(7-dodecyl-9H-fluoren-2-yl)-2,2′-bithiophene (DDFTTF). It appears that the edibility of DDFTTF has not been explicitly studied yet.[154] In this case, inexpensive, biodegradable and potentially edible polymer compounds such as PLGA and PVA,[224,225] previously used for a wide array of biomedical applications, have been exploited in the device architecture as a substrate and dielectric material, respectively. Solvent-free fabrication of a flexible nontoxic ambipolar all-carbon paper based FETs has been proposed by Kanaparthi and Badhulika.[226] The authors exploit a low-cost, nontoxic, recyclable, and biodegradable cellulose paper as both the substrate and the dielectric, and pencil graphite for all electrodes and for the active phase (Figure 5f). Recently, Bonacchini et al. suggested tattoo-paper transfer as a versatile platform for all-printed organic edible electronics.[21] The fabrication of inkjet-printed OFETs on untreated commercial tattoo-paper, and their subsequent transfer (Figure 5g) and operation on edible substrates with a complex nonplanar geometry was demonstrated. Different polymer semiconductors were used, such as poly(3-hexylthiophene (P3HT), poly[2,5-bis(2-decylnonadecyl)pyrrolo[3,4-c]pyrrole-1,4-(2H,5H)-dione-(E)-1,2-di(2,2′-bithiophen-5yl)ethene] (29-DPP-TVT), and poly{[*N*,*N*′-bis(2-octyldodecyl)-naphthalene-1,4,5,8-bis(dicarboximide)-2,6-diyl]-alt-5,5′-(2,2′-bithiophene)} (P(NDI2OD-T2)) in order to prove the versatility of the fabrication, transfer procedure, and the compatibility of the platform with both good hole and electron transporting materials. No data on the edibility of the adopted semiconductors was available, while preliminary cytotoxicity tests on different cells cultures did not reveal any adverse reaction. Interesting to note that P3HT, being for long time a prototypal polymer semiconductor for various optoelectronic applications and recently adopted successfully for bioactive interfaces and devices, is recognized as biocompatible.[227–229]

Another important contribution came by Bao and co-workers,[230] who developed FETs based on the biocompatible and totally disintegrable semiconducting co-polymer

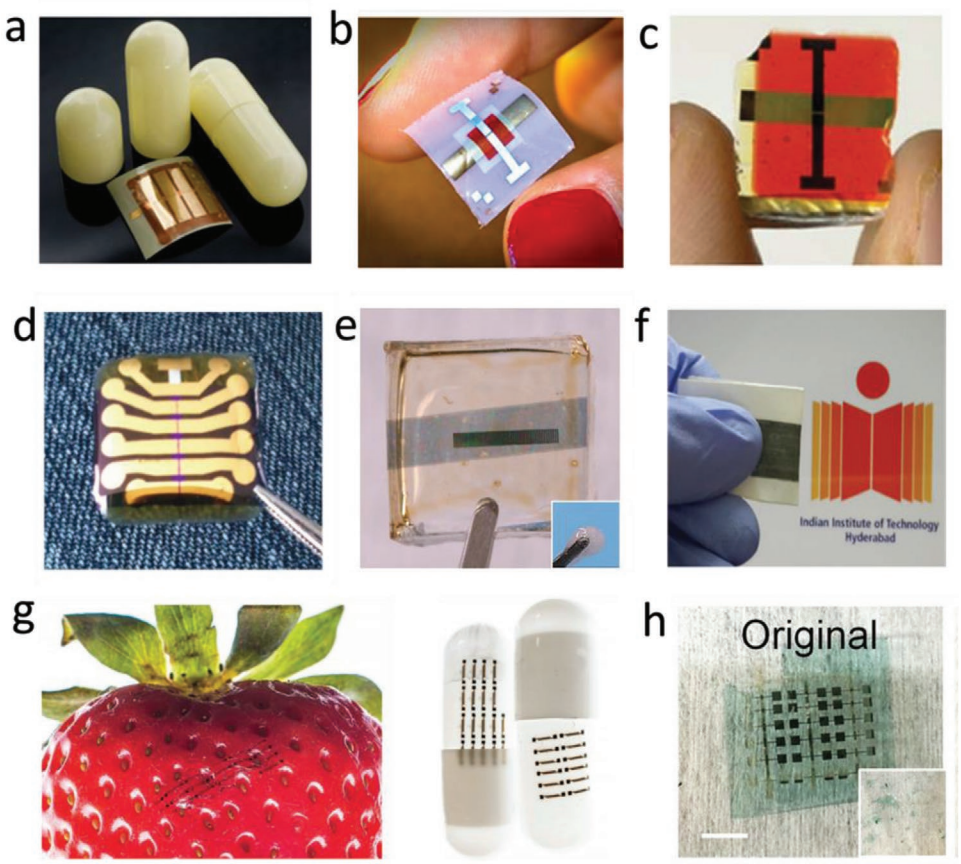

Figure 5. Examples of transistors fabricated entirely/partially from edible materials. a) OFET fabricated onto an edible hard gelatin capsule. The device consists of gold gate, source, and drain electrodes, adenine nucleobase gate dielectric, and indanthrene brilliant orange as an active semiconductor layer. Adapted with permission.[85] Copyright 2010, Elsevier. b) OFET on a biodegradable Ecoflex (BASF) plastic foil substrate treated with a smoothing layer of rosolic acid (aurin). The transistor consists of aluminum gate, source, and drain electrodes, adenine dielectric and cosmetic color perylene diimide semiconductor; μ_e = 0.01 cm^2 V^{-1} s^{-1}. Adapted with permission.[18] Copyright 2010, Wiley-VCH GmbH & Co. KGaA. c) OFET on caramelized glucose substrate. Gold serves as a gate, source, and drain electrode material, guanine and adenine form the gate dielectric and indanthrene yellow G is the semiconductor; μ_e = 0.012–0.015 cm^2 V^{-1} s^{-1}. Adapted with permission.[18] Copyright 2010, Wiley-VCH GmbH & Co. KGaA. d) Indigo-based ambipolar OFET, with good stability against degradation in air, fabricated on natural shellac resin substrate (photograph of five-transistors sample). Device architecture comprises an aluminum gate electrode, gold source, and drain electrodes, an aluminum oxide layer passivated by tetratetracontane as dielectric, and indigo pigment as an active material; $\mu_{e,h} = 1 \times 10^{-2}$ cm^2 V^{-1} s^{-1}. Reproduced with permission.[194] Copyright 2012, Wiley-VCH GmbH & Co. KGaA. e) Organic TFT fabricated on a resorbable PLGA biomaterial substrate. The device consists of silver gate electrode, gold source–drain contacts, PVA polymer gate dielectric and DDFTTF semiconductor. The blue square in the bottom right corner represents near total mass loss and 100% device hydration on the 70th day of in vitro degradation test. Reproduced with permission.[154] Copyright 2010, Wiley-VCH GmbH & Co. KGaA. f) Ambipolar flexible all-carbon FET on a low-cost, recyclable and biodegradable cellulose paper. Cellulose paper acts as both the substrate and dielectric; pencil graphite forms the source, drain, channel, and gate; $\mu_{e,h}$ = 167–191 cm^2 V^{-1} s^{-1}. Reproduced with permission.[226] Copyright 2016, Royal Society of Chemistry. g) Fully inkjet-printed OFETs on edible tattoo-paper substrate after the transfer onto food (strawberry) and pharmaceutical capsule. Temporary tattoo-paper consists of a sub-micrometric film of ethylcellulose (EC) attached to a paper sheet by means of a sacrificial water-soluble starch/dextrin layer. Electrodes were realized with a silver nanoparticle (AgNP) ink, EC acted both as transferrable substrate and as gate dielectric layer; various semiconductors were tested as active materials: P3HT blended with polystyrene ($\mu_h = 7 \times 10^{-3}$ cm^2 V^{-1} s^{-1}), 29-DPP-TVT (μ_h = 0.1 cm^2 V^{-1} s^{-1}), P(NDI2OD-T2) (μ_e in the range of 10^{-2} cm^2 V^{-1} s^{-1}). Reproduced with permission.[21] Copyright 2018, Wiley-VCH GmbH & Co. KGaA. h) Totally disintegrable transistors on an ultrathin biodegradable cellulose substrate. The device is composed of iron electrodes, alumina as a dielectric and PDPP-PD as semiconductor. The square in the bottom right corner represents a device at the third day of disintegration. Reproduced with permission.[230] Copyright 2017, PNAS.

polydiketopyrrolopyrrole-*p*-phenylene diamine (PDPP-PD), synthesized from natural sources. Transistors on sub-micrometer biodegradable cellulose substrates, with gold or iron electrodes and Al_2O_3 as the dielectric layer, showed good hole mobilities of 0.21 ± 0.03 cm^2 V^{-1} s^{-1} (0.12 ± 0.04 cm^2 V^{-1} s^{-1} in case of iron electrodes), with current on/off ratios >10^4 (Figure 5h). According to the authors, these electronics exposed to the pH of gastric acid in the human stomach (1.5–3.5) is likely to decompose. The only ingredients that might be potential hazardous following decomposition are aluminum, *p*-phenylenediamine (PPD) and diketopyrrolopyrrole (DPP) with introduced aldehyde groups. However, the content of these compounds in 1 cm^2 device is negligible, PPD is approved by FDA for use as a hair dye and DPP derivatives are widely used as pigments in industrial coatings, printing inks, and tattoos.

3.2.2. Electrolyte-Gated Transistors

Since the low voltage operation is the desired feature for the practical use of edible electronic components, the approach of electrolyte gating of FETs is of particular interest. Electrolyte gating is achieved with the use of an electrolyte, in form of a liquid, gel or solid, instead of the common solid-state dielectric in FETs. By application of a gate voltage, ions present in the electrolyte are displaced according to the imposed polarity, and accumulate at the interfaces with the gate electrode and with the semiconductor, forming electric double layers characterized by high capacitance in the range of μF cm^{-2}.[231] The interface with an organic semiconductor is likely to be permeable to ions, in which case an even higher volumetric capacitance develops. The latter case fells historically under the name of organic electrochemical transistor (OECT), although the fundamental mechanism is that of a volumetric field-effect.[232]

Gating of transistors with water can be considered a first example of devices with an edible electrolyte.[130,233] Horowitz and co-workers[129] demonstrated WGOFETs based on rubrene (no acute toxicity information is available) and P3HT semiconductors that operate at voltages lower than 1V (**Figure 6**a). Other groups as well provided a valuable input in the sector of WGOFETs exploiting different materials, including edible ones, in their design.[130,234] Using such devices as transducers opens up interesting opportunities for biosensor applications.

Strategies for electrolyte gated transistors with edible ionic gels like gelatin have been as well tested in electrolyte gated OFETs (EGOFETs)[235] and OECTs.[236] For example, Jo et al.[236] presented gelatin hydrogel-based OECTs (Figure 6b) with electrodes and transistor channel formed by poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS). Compatibility of PEDOT:PSS with body implants has been widely experimentally tested, while no information on its edibility is available.[237]

A more sophisticated electrolyte in a form of an alginate capsule (Figure 6c) for gating OFETs have been introduced by L. Torsi and collaborators.[133] The alginate system operates at voltages <0.5 V and was exploited for biosensing applications, in particular, for electronic detection of the glucose/glucose-oxidase reaction. Characterized by high biocompatibility and the

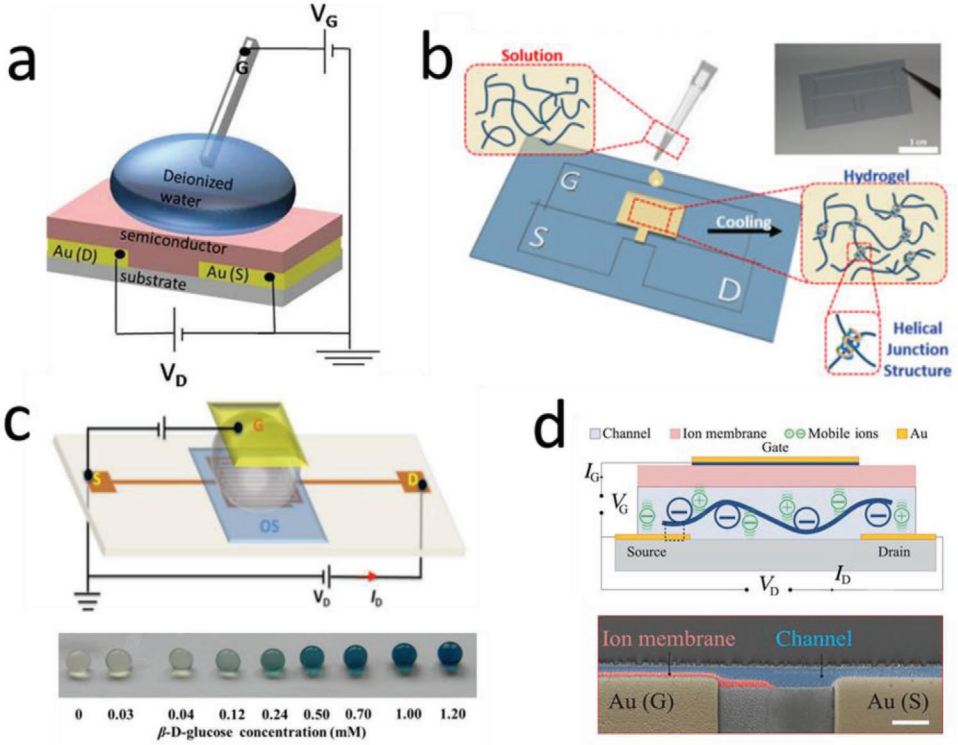

Figure 6. Examples of electrolyte-gated transistors fabricated primarily from potentially edible materials. a) A schematic cross-section of an OFET gated via pure water. Rubrene semiconductor single crystals were grown on a PDMS substrate equipped with gold source and drain electrodes. A gating water droplet is placed between the gold gate electrode and the active layer. Reproduced with permission.[129] Copyright 2010, Wiley-VCH GmbH & Co. KGaA. b) Schematic and photograph of a gelatin electrolyte-based OECT. Device consists of patterned PEDOT:PSS gate, source, and drain electrodes on a thin PET substrate. Three different kinds of additives, malic acid, NaOH, and sodium chloride were mixed with the gelatin hydrogel ionic layer. Reproduced with permission.[236] Copyright 2018, American Chemical Society. c) Alginate capsule gated OFET made of interdigitated gold source and drain electrodes on flexible PEN substrate, with a P3HT semiconductor ($\mu_h = 1.5 \times 10^{-2}$ cm^2 V^{-1} s^{-1}). Colorimetric assay (bottom inset) shows GOx/HRP alginate capsules incubated in solutions with different concentrations of glucose. The capsules turn into deeper color as the concentration of glucose increases. Reproduced with permission.[133] Copyright 2015, American Institute of Physics. d) Schematic illustration of IGT consisting of gold gate, source, and drain electrodes, a PEDOT:PSS channel combined with d-sorbitol and chitosan as an ion membrane. D-sorbitol creates an ion reservoir, maintaining mobile ions (green) that can travel within the channel. Cross-sectional scanning electron microscopy (SEM) image (bottom inset, scale bar: 5 μm). The additional PEDOT:PSS layer below the gate electrode is not visible in the SEM image. Reproduced with permission.[122] Copyright 2019, American Association for the Advancement of Science.

possibility to be easily shaped into several forms, the alginate system has potential to efficiently serve as an analyte delivery system as well as a micro bioreactor.

Khodagholy and co-workers[122] have developed an internal ion-gated organic electrochemical transistor (IGT) (Figure 6d) based on PEDOT:PSS characterized by biocompatibility, conformability, and air-stability. This type of transistor has mobile ions embedded in the conducting polymer of the device channel, creating a self-(de)doping process that eliminates the need for ion exchange from a shared external electrolyte. Mobile ions within the conducting polymer channel permit volumetric capacitance, relatively fast speed (effective bandwidth of 380 kHz) and high transconductance (≈32.30 mS). The architecture of the IGT can enable integrated real-time sensing and stimulation of signals in living organisms.

3.2.3. Toward Edible Electronic Circuits

Electronic circuits are necessary for signals conditioning and control in future edible systems. Here we introduce the most recent reports on edible and partially edible circuits, most of which are rather simple and reach the level of a single logic gate. Indeed, designing and fabricating circuits from edible materials is not straightforward due to the limitations the field is facing at the moment from the materials and processing points of view. Owing to this, one common strategy is to start realizing circuits combining fully edible components with additional not edible (or not yet proven to be edible) materials or elements to first prove some basic functionalities or sub-parts of the circuit. Such elements may find replacement with fully edible ones in the near future.

An approach utilizing food for the fabrication of the conductive interconnections in a circuit has been proposed by in het Panhuis and co-workers.[71] The authors 3D printed commercially available Vegemite and Marmite breakfast spreads (based on yeast extract) on bread substrates. The printed part was combined with other nonedible circuit components (LED and wires to an external power supply) in order to power up the LED through the printed edible line (**Figure 7**a).

Daniele et al.[238] reported the fabrication and characterization of a "sweet" polysaccharide circuit board as a decal for conformal electronic systems (Figure 7b). As a proof-of-concept, the group demonstrated a circuit making use of the edible board and common solid-state LEDs that exhibited ideal operation with a turn-on voltage at 5.4 V. Such boards were composed of nanofibril cellulose decal transfer and pullulan support that, along with gold traces and silver printed contacts, constitute the edible part of the circuit. Interestingly, pullulan is a maltotriose polysaccharide characterized by good film forming and it is in use in the manufacturing of candy films, food additives, and oral/transdermal drug delivery agents. These polysaccharides are attractive also for their aqueous processing and ability to withstand treatments with most organic solvents utilized during the fabrication.

Edible multilayered RC filters (Figure 7c) printed using a CB-based ink for conductors and an egg white based ink as a dielectric have been recently demonstrated by Le Borgne et al.[222] The −3 dB cut-off frequency of the filter was found to be 170 kHz; capacitance and resistance were measured to be 0.35 nF and 5 kΩ, respectively.

An edible RF filter, operating as a band reject filter, was proposed by Jiang and co-workers.[96] The filter was made completely by materials that can be safely ingested and assimilated as metabolized nutrients (Figure 7d).

More sophisticated circuits examples include integrated complementary inverters based on the aforementioned discrete transistors. For example, inverters built on ambipolar indigo and tyrian purple OFETs, characterized by a remarkable voltage gain in the order of 10^2, have been presented as a proof of the possibility to move toward robust edible logic circuits.[192,194] The authors employing the tattoo-paper transfer technique demonstrated the realization of all-printed robust complementary logic inverters transferred on a pharmaceutical capsule.[21]

Bao and co-workers[230] demonstrated disintegrable and biocompatible transient pseudocomplementary flexible circuits that are ultrathin (<1 μm) and ultralightweight (≈2 g m^{-2}). Such pseudocomplementary circuits are based on only one type of semiconductor, the decomposable PDPP-PD, exhibit high gain (≈13) and low voltage operation (4 V). Both fabricated NOR and NAND gates consisting of six transistors showed almost rail-to-rail voltage swings. Due to a good devices conformability, they can be easily transferred onto any target substrate (Figure 7e).

Circuits based on electrolyte-gated devices, comprising potentially edible electrolytes, were proposed as well. Jo et al.[236] extended the gelatin hydrogel-based OECT (Figure 6b) to electrochemical logic circuits (NOT, NOR, and NAND gates). It has been demonstrated that the pH of the gelatin hydrogel can affect the electrical conductivity of the PEDOT:PSS in the OECT, leading to the change in its resistance and output voltage. Consequently, the performance of logic gates becomes as well pH dependent.

IGTs-based scalable and conformable digital logic gates (NAND and NOR gates, Figure 7f), and cascaded amplifiers have been introduced by Khodagholy and co-workers.[122]

3.2.4. Light-Emission and Chromism

Color-changing and light-emitting devices can be developed using chromophores or luminescent materials that are able to change their optical properties (such as transmission, absorption, reflectance, and/or emittance) when a specific stimulus is applied to them. This stimulus can occur in a form of optical, thermal, electrical, chemical, or mechanical impact.

Electronic devices and systems that can emit, detect, or control light are appealing for a variety of possible edible electronics applications. Edible devices realized in a form of an electronic display can find use in environmental or agricultural testing, smart direct food tagging, health care monitoring, or simple sensors. In contrast to a well-established chemical indicator, electronic few pixels displays can provide the feedback from a diagnostic test and enable the integration of electronically encoded data in digitalized context for further communication, processing, and storage.

A number of possible solutions for potentially edible electronic displays have been suggested by several research groups,

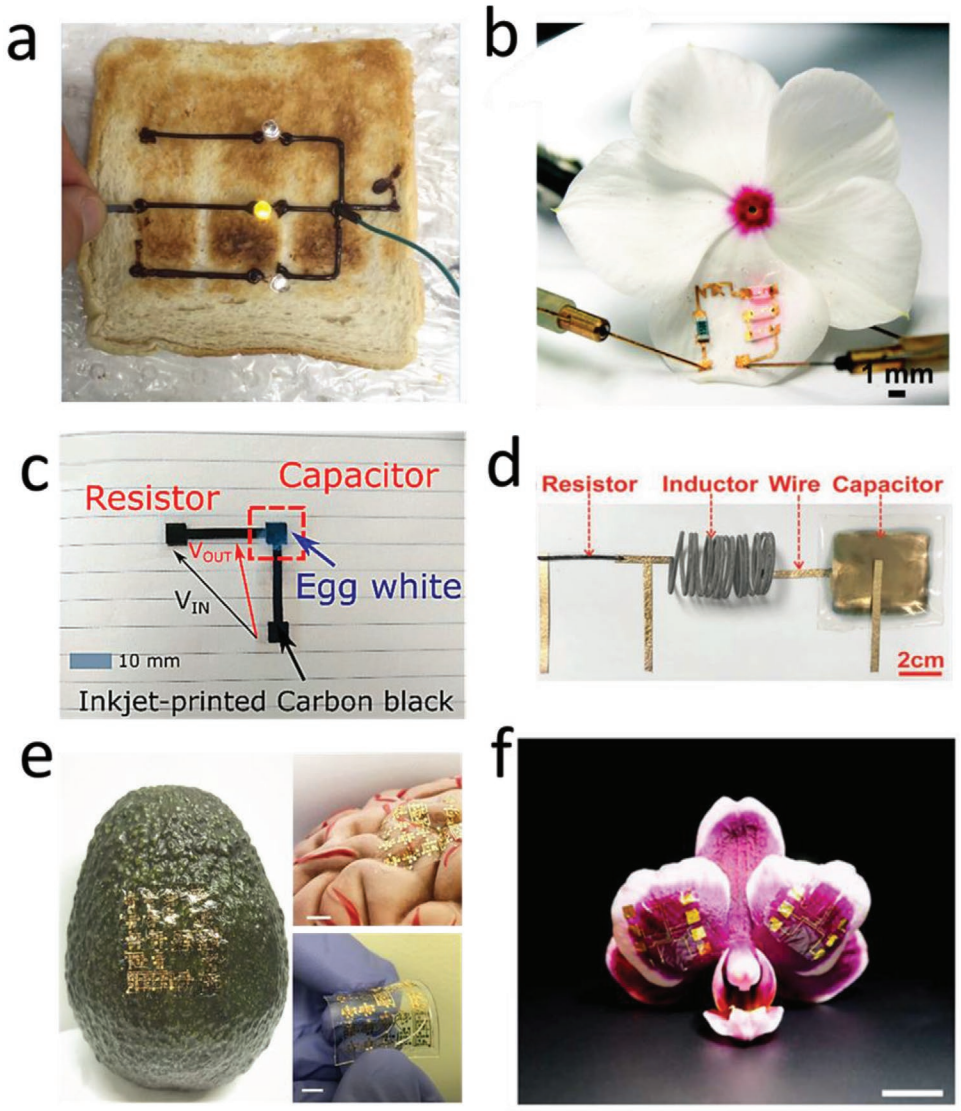

Figure 7. a) Photographs of a 3D printed Vegemite electric circuit extruded onto an edible (bread) substrate for powering nonedible light-emitting diodes. Reproduced with permission.[71] Copyright 2017, Elsevier. b) LED circuit fabricated on a polysaccharide circuit board based on nano-cellulose–pullulan decal. The pullulan support was dissolved in water, and the remaining nanofibril cellulose decal with conductive gold traces, silver printed contacts and additional electronics packages was transferred onto a flower leaf. Reproduced with permission.[238] Copyright 2014, Wiley-VCH GmbH & Co. KGaA. c) Optical image of the RC filter composed of an edible resistor and an edible capacitor in series. The resistor and the capacitor electrodes are made of inkjet printed carbon black. The egg white, used as dielectric in the capacitor, is screen printed. Reproduced with permission.[222] Copyright 2019, MDPI. d) A photograph of an edible RF filter on a rice paper substrate. The circuit consists of Au wires/interconnects, a resistor made of carbonized cotton candy and sweet potato starch, an inductor made of carbonized cotton and sweet potato starch, and an edible capacitor composed of gelatin as the dielectric material, and Au for the electrodes. Reproduced with permission.[96] Copyright 2017, Wiley-VCH GmbH & Co. KGaA. e) Disintegrable pseudocomplementary logic gates (Inverter, NOR, and NAND gate) on an ultrathin cellulose substrate. Circuits are based on PDPP-PD semiconductor, gold as the gate, source, drain and interconnects, and Al_2O_3 as the dielectric layer. Devices transferred onto the rough surface of an avocado, onto a human brain model and PDMS substrate (scale bar: 5 mm). Reproduced with permission.[230] Copyright 2017, PNAS. f) Integrated IGT-based digital logic gates (NAND and NOR) on parylene-C (not edible) conform to the surface of orchid petals (scale bar: 1 cm). For IGTs architecture please refer to Figure 6d. Reproduced with permission.[122]Copyright 2019, American Association for the Advancement of Science.

and ranges from OLEDs and lasers to electro-/thermo-chromic devices.

Tajima et al.,[239] for instance, have fabricated OLEDs from biomolecular edible compounds such as chlorophyll *a*, cytochrome *c*, myoglobin, hemin, and vitamin B_{12}. The developed indium tin oxide (ITO)/biomolecule/Al junctions showed values of quantum efficiencies of the order of 10^{-7} at 10 V.

Possible future of solution-processed Bio-OLEDs with an emission layer based on a riboflavin (vitamin B_2) derivative, RFLT, has been outlined by Hernandez-Sosa and co-workers (**Figure 8**a). The addition of tailored side groups that change riboflavin solubility enables the formation of homogeneous and smooth films from solutions. RFLT-based OLEDs demonstrated maximum luminance of 10 cd m^{-2} with turn-on voltages

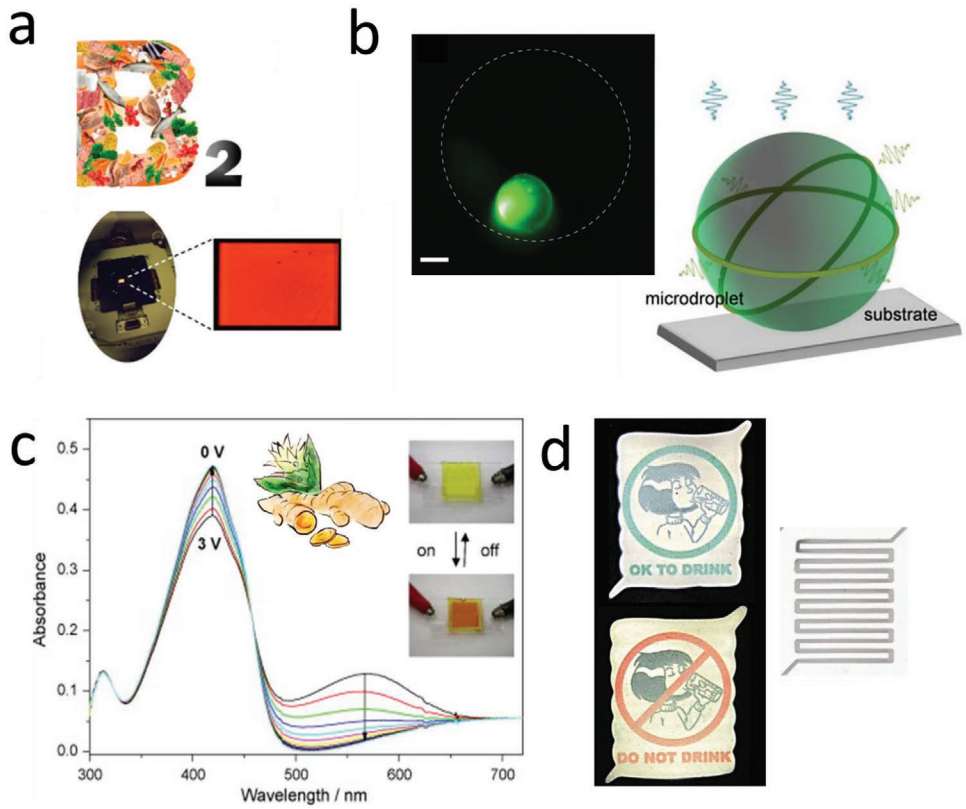

Figure 8. a) Solution-processed Bio-OLED based on RFLT (B_2 vitamin derivative). A micrograph of an operating 4 mm × 6 mm pixel is shown. The device architecture is the following: ITO/PEDOT:PSS/PVK/RFLT/Ag. The interlayer of poly(9-vinylcarbazole) (PVK) is introduced to assist with hole transport and electron blocking between PEDOT:PSS and RFLT. Reproduced with permission.[199] Copyright 2017, American Chemical Society. b) All-biomaterial laser based on vitamin microspheres embedded in PLLA microwells. FMN in glycerol-mixed microspheres is used as the gain medium. Vitamin microspheres with diameters of 10–40 µm were formed by spraying in situ and encapsulated in patterned superhydrophobic PLLA films. Left: a fluorescence (pseudocolor) image of a vitamin microsphere above lasing threshold (scale bar: 10 µm); right: 3D schematic of a spherical microdroplet laser. Reproduced with permission.[240] Copyright 2013, Wiley-VCH GmbH & Co. KGaA. c) Photo- and electrophysical properties of curcumin. The architecture of the electrochromic cell: ITO/curcumin-Bu_4NClO_4/ITO (conductor and electrolyte are not edible). A micrograph of an operating 3 cm × 3 cm pixel in the inset of the panel. Reproduced with permission.[245] Copyright 2010, Elsevier. d) Paper thermochromic displays as simple, low-cost, textual indicators for diagnostic tests (indication of the quality of drinking water, i.e., safe vs unsafe). The display is made of a thermochromic ink on photo paper, and Zn metallic wires patterned on the opposite side to serve as heating elements. Reproduced with permission.[251] Copyright 2013, The Royal Society of Chemistry.

of ≈11 V and a broad spectral orange exciplex emission, peaked at 640 nm.

The optical and electronic properties of naturally sourced, sustainable fungi-derived pigment (xylindein) have investigated in its pure state and in blend with crystalline nanocellulose.[205] The pigment exhibited high photostability, thermally activated charge transport and photoresponse to a 633 nm continuous excitation with activation energies of ≈0.3 eV. Toxicological studies of the material did not indicate any adverse effects. Therefore, xylindein and other fungi-derived pigments hold promise to be further implemented in edible optoelectronic devices.

A miniature laser fully based on GRAS biomaterials can suggest interesting solution for edible electronics applications. Nizamoglu et al.[240] realized vitamin B_2-doped microdroplet lasers on a superhydrophobic poly-L-lactic (PLLA) acid substrate (Figure 8b). The form of vitamin B_2, flavin mononucleotide (FMN, a biomolecule compatible with the human body, already present in many types of tissues including heart, liver, and kidney), embedded in glycerol-mixed microspheres, acts as a gain medium of the laser. An active photonic device supports lasing at optical pump energies as low as 15 nJ per pulse (≈1 kW mm^{-2}). Combined with biomarker molecules (e.g., glucose-responsive monomers), such biomaterial-based lasers can open broad opportunities for biosensing.

Materials with controlled chromism could be as well of potential interest for the development of the edible electronics platform. Electrochromic materials, in particular, are elements or compounds that can switch their optical properties between colored and bleached states reversibly or persistently through the activation of an electrochemical (redox) process when subjected to an electric field.[241] In electrochromic devices (ECDs), both electronic and ionic conductivities are exploited. Indeed, for the device operation, in addition to the electrochromic material, a (transparent) electron conductor and a good mobility electrolyte are needed in order to coordinate the chromism reaction. Their most feasible application concerns the food and pharmaceutical field, where the system operation takes

place out of the human body and in an environment in which light can reach the user. These devices could work as optical actuators in single pixels shape or for few-pixel displays, representing a simple and fast way to interface with the user.

The use of this technology as communication tool based on a visual feedback seems to be one the most viable, both for the low power consumption generally requested by these cells and also for the intrinsic electrochromic and ionic conductivity properties of some edible materials. Among them, Prussian blue, in addition to be a well-studied electrochromic material,[242,243] is also widely used in pharmacological applications in the form of Radiogardase insoluble capsules for the treatment against radioactive contaminants, as cesium or thallium.[244] Son and co-workers[245] reported electrochromic cells based on edible curcumin (E100) extracted from *Curcuma Longa* (Figure 8c). The cell was colored red at 3 V and changed to yellow in open-circuit condition. In some cases potentially edible materials have been proposed as electrolytes in electrochromic pixels, including, for instance, electrolytes based on DNA[246] or KCl (E508) aqueous solution.[243]

The main effort toward a bioinspired and green ECD also led to propose edible solid scaffolds for electrolytes (cellulose, PEG, DNA, and glycerol), but generally using toxic or not certificated ion species in the matrix.[246–248] Moreover, good electron conducting, transparent and safely ingestible materials have not been reported yet, and a great part of the literature report electrodes based on PEDOT:PSS or ITO. Finally, in the attempt to simplify the common ECD architecture, a simple structure was proposed, with the use of screen-printed silver electrodes sandwiching PEDOT:PSS, achieving transparency by introducing a silver patterned grid at the user-faced electrode.[249]

Other approaches that could be of interest, in the context of edible electronics, involve the use of halochromic or thermochromic materials as a visual communication strategy (e.g., for sensing technology). Thermochromic compounds, edible examples of which are not yet reported according to our knowledge, are able to change color as a function of temperature.[250]

Whitesides and co-workers developed a biodegradable and disposable thermochromic display/sensor on paper (Figure 8d). Although the display is based on leuco dyes (dispersed in a PMMA matrix with a 7.4 wt% concentration), not yet classified as edible but present in thermochromic nail polishes found in the market, the approach could be of inspiration for further development of edible thermochromics. Joule heating of an edible Zn conductive wire driving the thermochromic ink from colored to transparent is at the core of the device concept. An example of a nontoxic thermochromic composite that consists of the biopolymer PLA, a natural dye of the anthocyanidine class, a gallate (E310) derivative and a fatty acid,[251] was also proposed.

It is worth mentioning that there is a wide database of edible halochromic materials able to colorimetrically respond to the change of pH, among which it is possible to find indigo carmine, methylene blue and anthocyanins.[252]

3.3. Sensors

Sensing technology plays an indispensable role in the development of edible electronics toward applications. Thanks to a strong progress in sensing technologies, a variety of environmentally friendly, disposable, and biodegradable sensors have been proposed, some of which have been already integrated into our daily lives.[47,103,253–257]

The development of electronic sensors fully made by edible materials is still, however, in its infancy, with only few, but ambitious examples available. Considering both in- and out-of-body operation, edible sensors extend from rather simple physical pressure, temperature, and pH sensitive devices to more complex systems targeting electrochemical detection of organic/biological compounds and gases. Here we report on recent relevant examples of partially edible, hybrid sensing systems that could serve as a basis for future all-edible systems by replacement of nonedible components.

3.3.1. Sensors for in Body Operation

In-body operation of the edible sensing system is foreseen mainly for biomedical applications. Edible electronics in the form of ingestible sensors opens up broad opportunities for theranostics and monitoring of physiological conditions of the GI tract through, for example, direct real-time measurement of pH[46] and gases,[20] characteristic GI biomarkers,[44] GI motility,[47] luminal bacterial content,[2] GI bleeding,[8,44] drug concentrations, and adherence.[11,12,258]

In the work by Jiang and collaborators,[96] authors demonstrate that food-based and nutritive materials can enable the fabrication of functional edible devices intended for wireless pH monitoring. The operation principle of an edible pH sensor, fabricated on a sugar paste substrate (**Figure 9**a), is based on the change of the capacitance and consequent shift of the resonant frequency of a coil upon variation of the pH value. The device was tested in vitro exposing the sensor to sample solutions with a known pH, and revealed responsivity to pH values of both acidic and basic solutions in the range from 1 to 12.

Sensing pressure within the GI system is important for monitoring its health status and, in particular, for preventing the build-up of dangerous internal forces in alimentary tract. Consequently, the demand for in-body pressure measuring devices led to the development of piezoelectric and capacitive pressure sensors. The piezoelectric microphone proposed by Jiang and co-workers,[96] further discussed in Section 3.5, is based on an edible 2 mm thick film formed by broccoli powder and gelatin. It was successfully used to record low-frequency abdominal sounds associated with both normal and pathological conditions. The coupling coefficient d_{33} of the edible piezoelectric film was found to be 4.3 pC N^{-1}, a value close to 5 pC N^{-1} obtainable with ZnO,[259] a recognized piezoelectric material, which is GRAS listed. Nguyen et al.,[260] introduced an ingestible piezoelectric force sensor (Figure 9b) to detect biophysiological forces. The device design relies on safe medical materials approved by FDA, comprising edible Mg or Mo, PLA, and PLLA. The sensor can precisely measure pressures in a wide range, from 0 to 18 kPa, and provide a reliable operation for a period of 4 days in an aqueous environment. Capacitive sensing has been as well exploited in a variety of potentially edible devices. M. in het Panhuis and co-workers[73] reported the sensor in a form of gellan gum/gelatin ionic-covalent

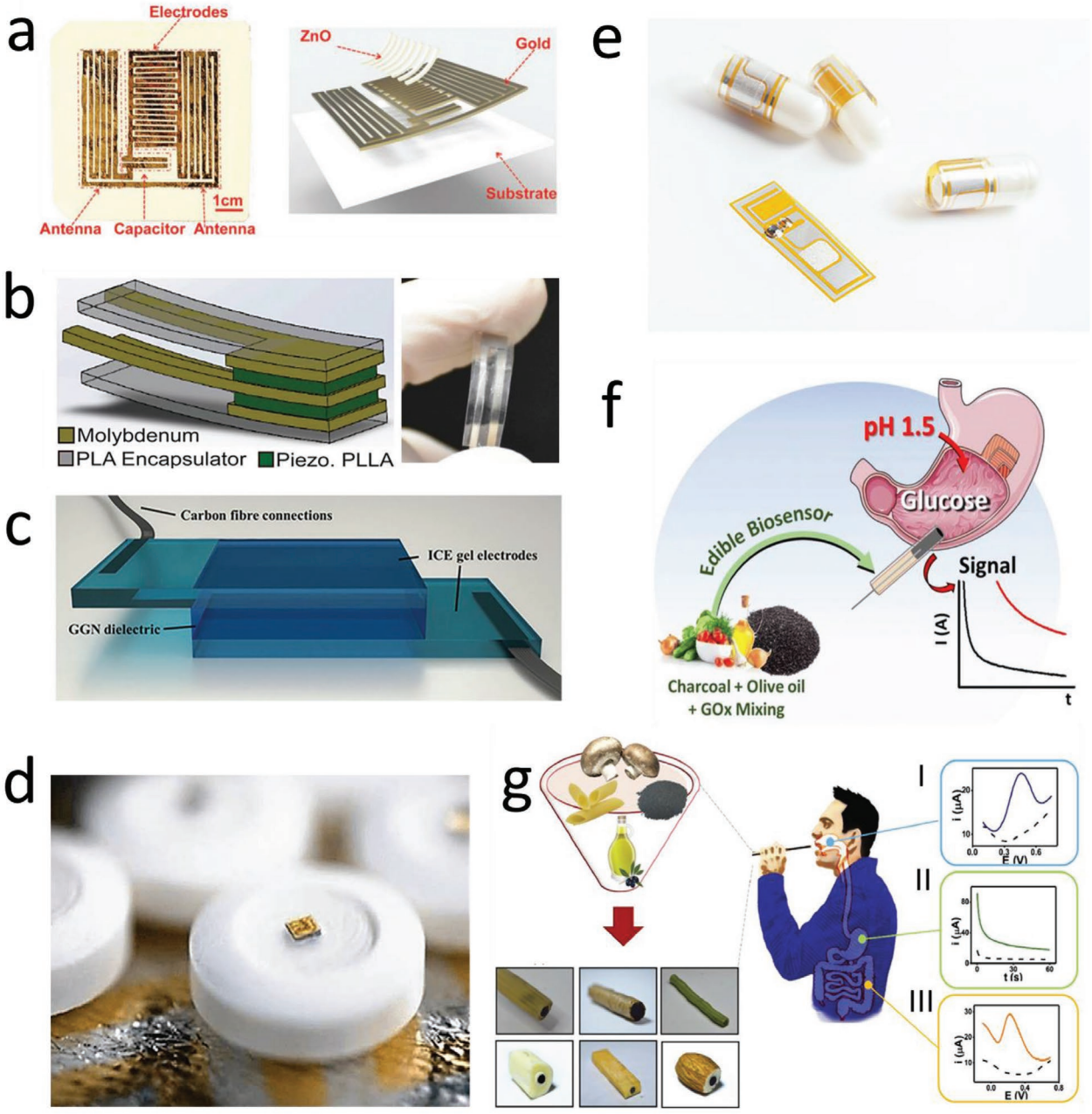

Figure 9. Potentially edible sensors for in-body operation. a) Photograph and illustration of an edible pH sensor on a sugar paste substrate. Sensor is made of Au–ZnO, connected to an Au antenna for wireless signals transmission and an edible capacitor made of thin gelatin sheets coated with edible Au. Reproduced with permission.[96] Copyright 2017, Wiley-VCH GmbH & Co. KGaA. b) Biodegradable piezoelectric PLLA pressure sensor. The sensor structure includes two layers of piezoelectric PLLA, sandwiched between Mo or Mg electrodes, and a PLA encapsulation (left); optical image of a fabricated biodegradable piezoelectric PLLA sensor (right); the device dimensions are 5 mm × 5 mm, with a thickness of 200 µm. Reproduced with permission.[260] Copyright 2018, PNAS. c) Schematic of a capacitive pressure sensor. The device consists of ionic-covalent entanglement (ICE) hydrogel electrodes based on gellan gum and gelatin, carbon additional connections and dielectric prepared from 10% w/w genipin to gelatin hydrogel. Reproduced with permission.[73] Copyright 2017, The Royal Society of Chemistry. d) Photograph and schematic of ingestible Abilify MyCite sensor embedded in a tablet (the full list of the materials can be found in ref. [266]). Reproduced with permission.[1] Copyright 2015, Elsevier Ltd. e) The gelatin ID-Capsule containing the ingestible sensor with an RF tag that activates in contact with gastric acids. The digital pill has the size of an 800 mg ibuprofen tablet. The ID-Tag is composed of an integrated circuit (Ag traces, Mg, and AgCl electrodes) on a flexible film. Reproduced with permission.[267] Copyright 2020, etectRx. f) Edible electrochemical biosensors for direct and controlled glucose sensing in gastrointestinal fluids of different pH ranges (gastric, pH 1.5 and intestinal, pH 6.5). The sensors are based on GOx enzyme protected from the harsh acid conditions by the matrix of activated charcoal conductor and olive oil binder. Reproduced with permission.[268] Copyright 2020, Wiley-VCH GmbH & Co. KGaA. g) Food based electrochemical sensors. The electrodes are made of edible activated charcoal, edible food sleeves (penne, cookie, green bean, milk candy, cheese, and almond), and olive oil. Electrochemical data: detecting i) salivary uric acid (0.5×10^{-3} M) in artificial saliva using penne electrode; ii) ascorbic acid (0.2×10^{-3} M) in artificial gastric fluid using candy electrode; and iii) dopamine (0.4×10^{-3} M) in artificial intestinal fluid using almond electrode. Reproduced with permission.[106] Copyright 2017, Wiley-VCH GmbH & Co. KGaA.

entanglement hydrogel (Figure 9c) that displayed a sensitivity of 0.80 ± 0.06 pF kPa^{-1} up to 20 kPa. Since the pressure exerted by the GI tract on its content is typically from 0.7 to 6.3 kPa, authors highlight that the sensor can be employed for detection of digestive pressure abnormalities such as intestinal motility disorders.

Another example of capacitive wireless pressure sensor has been suggested by Bao et al.[103] Made of entirely biodegradable, biocompatible materials, some of which are also edible or potentially edible (e.g., Mg, poly(glycerol sebacate) (PGS), PLLA), the proposed device, originally intended for measuring arterial blood flow, could be adapted to potentially perform its function within the GI system. A microfabricated biodegradable wireless RF pressure sensor based on the passive resonant mechanism, have been introduced by Luo et al.[261] The sensor consists of edible zinc/iron conducting patterns that form inductor coils and capacitor plates. PLLA is used as the packaging and pressure-sensing material because of its good mechanical properties, and PCL is utilized as a bonding and sealing material.

Another important task of biomedical research, clinical practice, and drug development, is the real-time monitoring of the ingestion events. To this aim, systems such as Proteus Discover[11] (Figure 9d) and ID-Cap[258,262–264] by etectRx (Figure 9e) that have already been FDA cleared for oral use, could be of inspiration for further realization of fully edible systems. These devices are intended to be incorporated with pharmaceutical tablets or capsules, have been demonstrated to be biocompatible and nontoxic, to pass through the digestive system intact, and to be excreted in the feces. Even though they are not entirely edible, they utilize some edible materials (e.g., magnesium, silver/gold, copper) in their design. Such sensors can monitor adherence to medications by communicating ingestion events data to the patient or healthcare provider. Combining the functions of power generation and communication in a small, safe, and inexpensive form factor, the proposed wireless sensors are also able to function in a wide range of fluids present in the stomach. Apart from medication adherence monitoring, the introduced systems offer the possibility of measuring hydration and fat content of the body, and can potentially represent a platform for "smart" targeted drug delivery.

Another sensing approach has been suggested by Wang and co-workers,[106,265] who first demonstrated completely food-based electrochemical sensors for measuring important electroactive biomarkers. As an example, the group has fabricated edible electrochemical biosensors for direct glucose sensing in gastrointestinal fluids of different pH ranges and compositions[265] (Figure 9f). The devices have been proved to be remarkably acid resistant and displayed a linear response between 2×10^{-3} and 10×10^{-3} M glucose with sensitivity depending on the pH of the GI fluid. pH-responsive enteric coatings have been exploited in order to stimulate a controlled activation of the sensor in a specific GI fluid at a desired time, what holds a potential for further development of sensing capsules passing through the different segments of the GI tract. In another work by Wang and collaborators,[106] the authors used olive-oil based edible carbon electrodes for electrochemical voltammetric detection of catechol, uric acid, ascorbic acid, dopamine, and acetaminophen (Figure 9g), and performed sensitive measurements in simulated saliva, gastric fluid, and intestinal fluid. In addition, mushroom and horseradish vegetable tissues were incorporated with edible carbon pastes for imparting biocatalytic activity toward the biosensing of phenolic and peroxide compounds. Furthermore, reported by the same authors, fully edible biofuel cells (discussed in Section 3.4.3) hold a great promise as smart self-powered ethanol biosensors.[95]

3.3.2. Sensors for Out-of-Body Operation

A discussion about edible sensors cannot be complete without mentioning out-of-body operation. This class of edible sensors is intended to address mainly food safety concerns, an increasingly important public health issue for both the consumer and food industry. Some approaches toward food quality control by means of edible sensors have been already proposed by a number of research groups.

Notably, in 2012 Omenetto and co-workers[19] demonstrated silk-based conformal, adhesive, edible food sensors (**Figure 10**a–c) in a form of wireless passive antennas for the monitoring of food conservation status. Made of only a submicrometer thick gold antenna or an array of antennas/resonators, such edible sensors were successfully proved to detect ripening, bacterial contamination and spoilage processes of food items like bananas, cheese, and milk. The sensor is either in the surface contact with the product (fruit skin) or immersed in the tested liquid (milk), and its sensing principle is based on the variation of resonant response of the antenna to dielectric changes associated with density/firmness and material composition. The latter can be affected by parameters like moisture, gas emission, salt content, and bacterial contamination, directly correlated to the quality of food. An external reader is then inductively coupled to monitor modification in the resonance frequency and signal amplitude.

Another interesting approach (as well appealing for in-body operation, in perspective) exploits edible silk-based materials.[269] In vivo use of an RF sensor mounted on tooth enamel was demonstrated to perform wireless monitoring, e.g., of food and liquid consumption, in the oral cavity (Figure 10d). Interlayers composed of silk films swell and absorb the surrounding solvent, changing thickness and dielectric constant, thus resulting in a change in resonant frequency of the sensor. These devices can become sensitized to a wide variety of fluid parameters such as alcohol content, salinity, sugars, pH, temperature, with the opportunity of adding more specifically functionalized layers for targeted sensing.

Güder and co-workers[270] introduced very cost-effective and environmentally friendly sensors based on cellulose fibers to detect water-soluble gases such as ammonia, trimethylamine, carbon dioxide, among others, with a very low limit of detection (e.g., 200 parts-per-billion for NH_3) and a fast and reversible response (Figure 10e). The intrinsic hygroscopic characteristics of cellulose paper (≈5% water content by weight at a relative humidity of 50%) enable a wet chemical sensing mechanism. Water-soluble gases can increase the ionic conductance of the paper substrate, thus providing the mechanism for sensing. The introduced sensor can be integrated into food packaging to monitor products freshness or implemented into

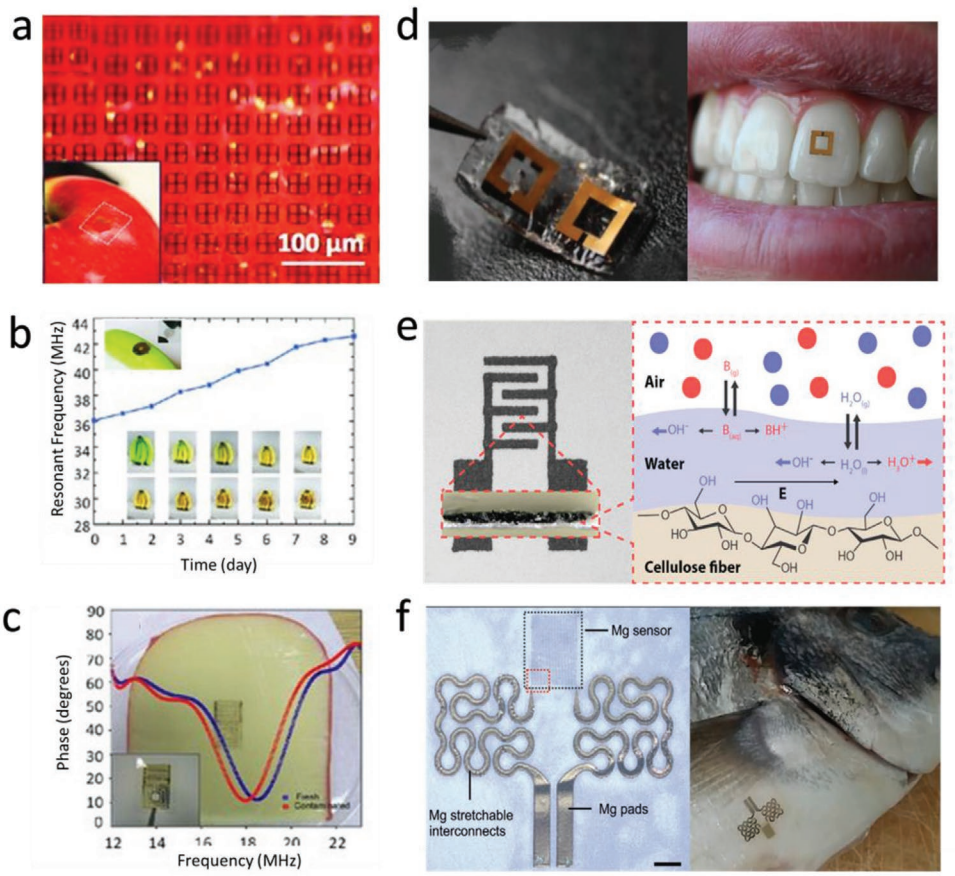

Figure 10. Potentially edible sensors oriented toward out-of-body operation. a) Silk-based conformal, adhesive, edible food sensors. The sensor consists of an antenna or an array of antennas/resonators made of sub-micrometer thick gold. The resonators are fabricated on pure-protein silk film substrates. b) A silk RFID-like antenna attached to a banana; experimentally measured time-dependent resonant frequencies of the antenna during banana ripening. c) Frequency-dependent impedance phase angle of a silk sensor applied to a slice of cheese to detect bacterial contamination. Reproduced with permission.[19] Copyright 2012, Wiley-VCH GmbH & Co. KGaA. d) Functional, RF-trilayer sensors for tooth-mounted, wireless monitoring of the oral cavity, and food consumption. A sensing active interlayer of a porous silk hydrogel film is sandwiched between layers of micromachined silk fibroin-gold split-ring resonators. The size of passive dielectric sensors is 2 mm × 2 mm. Trilayer sensor can adhere to human teeth for in vivo monitoring of ingested fluids. Reproduced with permission.[269] Copyright 2018, Wiley-VCH GmbH & Co. KGaA. e) Cellulose paper-based electrical gas sensors with printed carbon electrodes and the model of the sensing mechanism for an alkaline test gas ($B_{(g)}$). The interconnected network of cellulose fibers within paper is covered with a thin film of water, which is in equilibrium with the relative humidity and any gas present. Reacting with water, the dissolved gas ($B_{(aq)}$) dissociates to generate cations (BH^+) and hydroxide anions (OH^-). The generation of additional ions directly impacts the ionic conductivity of the device. Reproduced with permission.[270] Copyright 2019, American Chemical Society. f) Optical image and architecture of a fully biodegradable resistive temperature sensor. A thin Mg film (250 nm) constitutes the active layer, sandwiched between two dielectric layers of Si_3N_4 and SiO_2 and two films of Ecoflex acting as substrate and top encapsulation (scale bar 1 mm). Sensor photograph when laminated on top of a fish skin (right). The total weight of the device is less than 10 mg. Reproduced with permission.[271] Copyright 2017, Wiley-VCH GmbH & Co. KGaA.

near-field-communication tags to function as wireless, battery-less gas sensors that can be interrogated with smartphones.

Tröster and co-workers[271] proposed fully biodegradable temperature sensors also exploiting edible components in their design. Edible Mg microstructures have been utilized as an active layer of the sensor and encapsulated by a compostable-certified flexible Ecoflex polymer (Figure 10f). The sensor exhibits a linear response over a large range of temperature (from 20 to 50 °C) without any hysteretic behavior. The extracted temperature coefficient is 2.45×10^{-3} K^{-1} and the absolute sensitivity is 70 Ω K^{-1}. The layout and ultrathin format of the sensor confer a dynamic response of 10 ms and high mechanical stability, suggesting possible applications in food tracking.

Other examples reported in literature regarding edible food gas sensors that we would like to highlight exploit chemical pH sensitivity of the materials.[127,252] Specifically, sensors for food freshness based on pectin and red-cabbage, which are sensitive to a series of synthetic amines including ammonia, cadaverine and pyridine, demonstrated clear colorimetric changes as the food samples (beef, chicken, shrimp, or fish) degraded.[252] Other edible and pH-sensitive bilayer films were developed, including gelatin incorporated with ZnO as the top layer, and gellan gum incorporated with mulberry anthocyanins extract as the bottom layer.[127] Mulberry anthocyanins presented a remarkable color change, turning from pink to colorless at pH 2–6, from light green to yellow-green at pH 7–10, and becoming orange at pH 10–12. The composite bilayer films

demonstrated color stability under visible and UV light, electrochemical writing property, and the ability to indicate fish spoilage, showing a pink-to-green-to-yellow color change after exposure to different concentrations of NH_3.

3.4. Power Supply: Energy Storage Devices and Harvesting Technologies

Powering edible electronic devices is a formidable challenge. An efficient power supply embedded in the device is essential for the operation of most of the envisioned edible systems, as passives solutions may cover only part of the visionary applications. Beyond the need to find nontoxic materials, one of the main problems in the design of edible power supplies is correlated to their size and weight. It remains a fundamental challenge to reduce dimensions both to be compatible with integration into a microelectronic system, easy to be swallowed, and to minimize the quantity of ingested material, limiting the risk to exceed ADI values. Indeed, edible power supplies so far proposed need bulky structures in order to achieve acceptable energy density levels and output voltages, and the performances are not yet comparable to well established harvesting and batteries technologies used in nonedible electronics. On the other side, compared to the standard technologies on the market, requirements are less stringent in terms of performances and shelf life. For edible applications the target lifetime is governed by the approximate residence time in the gut, suggesting a power supply able to support device operation for approximately 10–100 h.[272] While for uses in perishable food industry applications, expiration date becomes the lifetime limit, setting an horizon time of operability up to few weeks. Moreover, high energy and power density are not needed in many applications where only few parameters have to be acquired and transmitted. The need for low-voltage outputs, limiting the microshock risks related to devices designed to operate along the GI tract, inherently reduces the overall power consumption.

To date, virtually all ingestible electronics has been powered primarily by using on-board batteries or galvanic cells.[11] Apart from that, supecapacitors represent another promising solution for power supplies. Overall, harvesting chemical energy from food or kinetic energy from gastric transit appears as the most promising approaches for powering edible electronic devices. However, many of these early-stage concepts will require improvements in stability and specific power generation before they can be successfully translated into practical applications.

Powering devices by external harvesting source is also compelling. RF powering appears to be a good candidate along with acoustic and ultrasounds technologies being also proposed to transfer energy to implanted medical devices.[273] However, practical challenges remain: for example, external equipment must be precisely oriented and guarantee a good energy transfer to the device placed deep in the body. These intrinsic physical limitations pose technical challenges that make practical implementations complicated. All these strategies can also be exploited for powering edible devices operating out of the body. In this context the size constraints are less stringent and the environmental conditions are not as harsh as in the gastric tract.

Here we present the principal technologies for energy storage (batteries, supercapacitors, and fuel cells) and energy harvesting, focusing on devices with a direct or potential application in the edible electronics field. Even though these approaches are discussed individually and can operate as self-standing supplies, their cross integration can be beneficial, as the one often proposed between energy harvesters and batteries or supercapacitors.

3.4.1. Batteries for Powering Edible Electronic Devices

Batteries are used extensively to power commercially available ingestible electronic devices for applications such as capsule endoscopy and therefore remain the gold standard for on-board energy storage. Batteries are advantageous for on-board energy storage because they typically have low self-discharge rates and can operate stably in many conditions found within the gut. Batteries serve a specific function, yet comprise a disproportionate amount of the material in a prospective edible electronic device. For example, batteries can comprise up to 50% of the mass in a device such as an ingestible camera (**Figure 11**a).

Many early examples of ingestible electronic devices use silver/silver oxide (Ag/AgO) batteries as on-board power supplies. Despite the comparatively low specific capacity, Ag/AgO is a logical choice to power ingestible devices because the electrode materials and electrolytes are nontoxic, while modest cell voltages limit the risk of tissue damage if the hermetic seal is breached. Battery chemistries that use aqueous electrolytes and nontoxic ions may have applications in edible electronic devices.[274,275] Aqueous electrolytes could permit the operation of open electrochemical systems within the GI tract. This concept could eliminate the need for hermetic seals as well as encapsulation materials. Additionally, it is advisable to consider using electrochemical cells that use endogenous cations, adequate charge storage capacities, and operate at voltages within the water window at physiological pH (1.2 to –0.4 V vs standard hydrogen electrode (SHE)). For example, aqueous sodium-ion chemistries cannot match the performance of lithium-ion counterparts, but are attractive for use as batteries to power edible electronic devices.[97] Unfortunately, currently, lithium salt-based batteries are not suitable for edible applications. Mostly, this derives from the presence of nonedible organic solvents, ceramic compounds, and polymeric gels used as electrolyte, in addition to the severe safety hazards (fire and gases) in case of improper handling. However, lithium itself is a well-known, cheap, and unpatented drug for the treatment of bipolar disorder, though it toxicity profile is not really well defined.[276]

Alternative battery chemistries that use either magnesium or potassium ions may also be useful in future design concepts.[277] There are many viable alternatives to lithium-ion batteries because, unlike many applications in consumer electronics or electric vehicles, primary cells are suitable candidates for the power requirements of edible electronic devices that operate for comparatively short timelines in single-use applications. In addition to the electrolyte and the ion, electrode composition is another important material design and selection criteria. While many electrodes in high-performance batteries use potentially toxic elements such as cobalt, there are many other electrodes

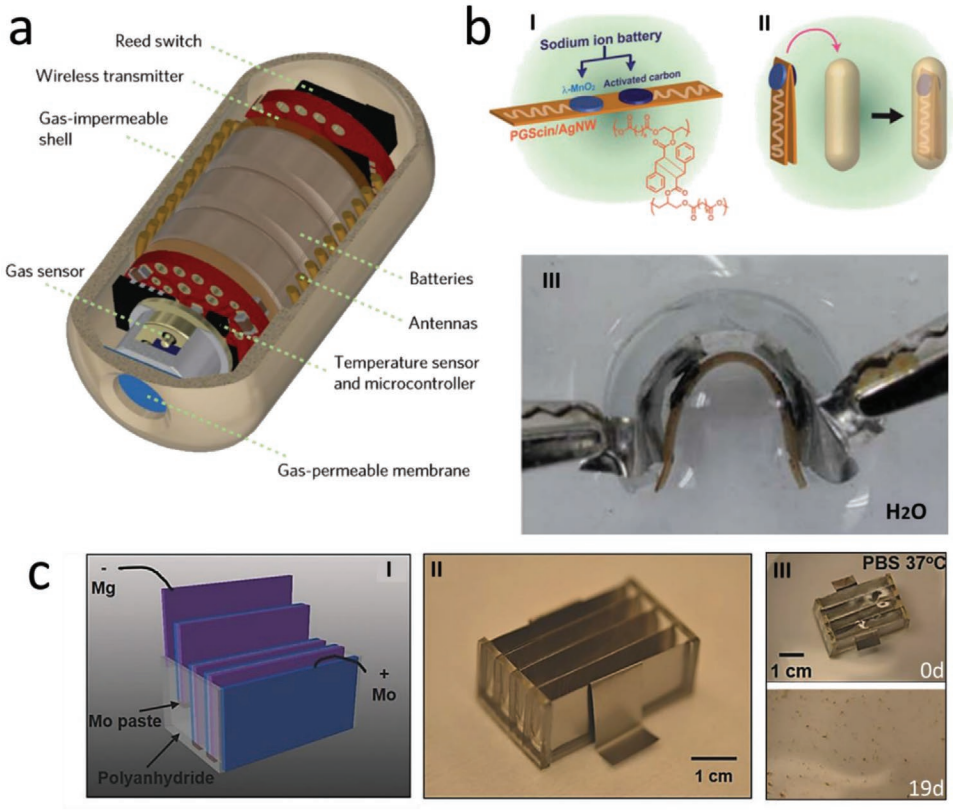

Figure 11. a) Rendering of an ingestible electronic capsule for the sensing of different gases in the GI tract. It comprises three button cell silver oxide batteries. Adapted with permission.[20] Copyright 2018, Springer Nature. b) i) Rendering of a biodegradable sodium battery on a poly(glycerol-*co*-sebacate)-cinnamate-silver nanowire (PGScin–AgNW) electrodes; ii) rendering of the device fitting in a size 000 capsule; iii) photograph of the device, with PGScin–AgNW electrodes swelling in water. Adapted with permission.[107] Copyright 2013, The Royal Society of Chemistry. c) i) Rendering of the biodegradable battery pack, composed by four Mg–Mo cells in series; ii) photograph of the battery pack; iii) degradation test over 19 days. Adapted with permission.[281] Copyright 2014, Wiley-VCH GmbH & Co. KGaA, Weinheim.

that use benign carbon-based compounds or transition metals that also provide a nutritional value.[97,110] For example, active carbon and λ-manganese oxide have been used as anode and cathode electrodes, respectively, in a biodegradable and flexible sodium ion battery. Such battery achieved output currents in the range of 5–20 µA and a potential up to 0.6 V, with storage capacities of 9.58 ± 0.7 mAh g^{-1} (were the weight unit refer to the active carbon mass,[107] Figure 11b).

Melanin-based pigments have also been exploited as electrode materials in aqueous sodium-ion systems because they support both capacitive and redox energy storage mechanisms and can degrade within the GI tract.[278] Aqueous sodium-ion cells composed of redox active melanin anodes and manganese oxide cathodes have charge storage capacities of 16 mAh g^{-1} compared 8 mAh g^{-1} for anodes without redox reactions.[97] Melanin pigments can be used as cathodes in primary cells and can achieve a charge storage capacity of up to 60 mAh g^{-1}.[110,277] These capacities are comparable to other aqueous electrochemical cells that use ceramic manganese-based electrodes.[274,279] Melanin-based cells can satisfy the power requirements of various medical devices including sensors and drug delivery pumps.[280]

Other options for on-board energy storage include galvanic couples using nontoxic metals. Thin film Mg anodes (8 µm thick, 7.9 µg) coupled with Cu cathodes (7 µm thick, 7.1 µg) produce open circuit potentials of 1.85 V and in vivo discharging current of 0.1 mA for a battery lifetime of ≈4 min.[11] These parameters are sufficient for the specific application of edible sensors to monitor patient compliance.[11] Galvanic cells composed of Mg and Cu are well within the acceptable daily limit of these minerals. This architecture does not include any electrolyte in the fabrication process: the electrochemical cell starts its galvanic corrosion when in contact with the gastric fluid. Also Mg and AgCl were used as electrochemical cell electrodes for a similar purpose.[258] Galvanic cells can also be constructed using Mg coupled with other cathode materials including Mo, W, and Fe[281] (Figure 11c). The operating voltages of Mg–Mo, Mg–W, and Mg–Fe are 0.7, 0.65, and 0.45 V, respectively. These electrochemical potentials are within the water stability window and therefore safe for ingestion. The choice of battery or galvanic cell composition for powering edible electronic devices is ultimately an optimization that balances operating voltage, gravimetric and/or volumetric capacity, and potential risk to the patient.

3.4.2. Supercapacitors

Supercapacitors, characterized by rapid recharging time and high power delivery, represent another promising strategy for

energy storage. In supercapacitors, the capacitive energy storage is given by the contribution of the static double layer capacitance and by pseudocapacitance that originates from reversible and fast faradaic redox and/or from ion intercalation in the electrodes.[282] The amount of charge stored is proportional to the electrodes surface area, and for this reason highly porous materials, as activated carbon, are often exploited. Since the storing process is not linked to slow electrochemical dynamics, the power density of supercapacitors is higher than in batteries, with the drawback of a lower energy density and voltage output. Their current lower autonomy is a limitation for continuous and long-term monitoring applications, where batteries remain a better solution. On the other hand, they are excellent candidates for powering cheap devices that require low operation time. Moreover, thanks to their fast charging time and long lifecycle, they can be exploited as rechargeable energy storages in combination with energy harvesters.

This class of energy storage devices lend themselves to sustainable energy applications, with numerous proposed devices incorporating green materials as electrodes and aqueous solution as electrolyte. Basswood was for example used as scaffold and functional material in electrodes (in its carbonized state) and separator layer for the fabrication of supercapacitors with low environmental impact[283] (**Figure 12**a). Such an example represents a bioinspired and versatile platform composed by nontoxic materials that might find its place in edible applications.

Other examples proposed for environmentally friendly and sustainable applications can fall unintentionally in the edible

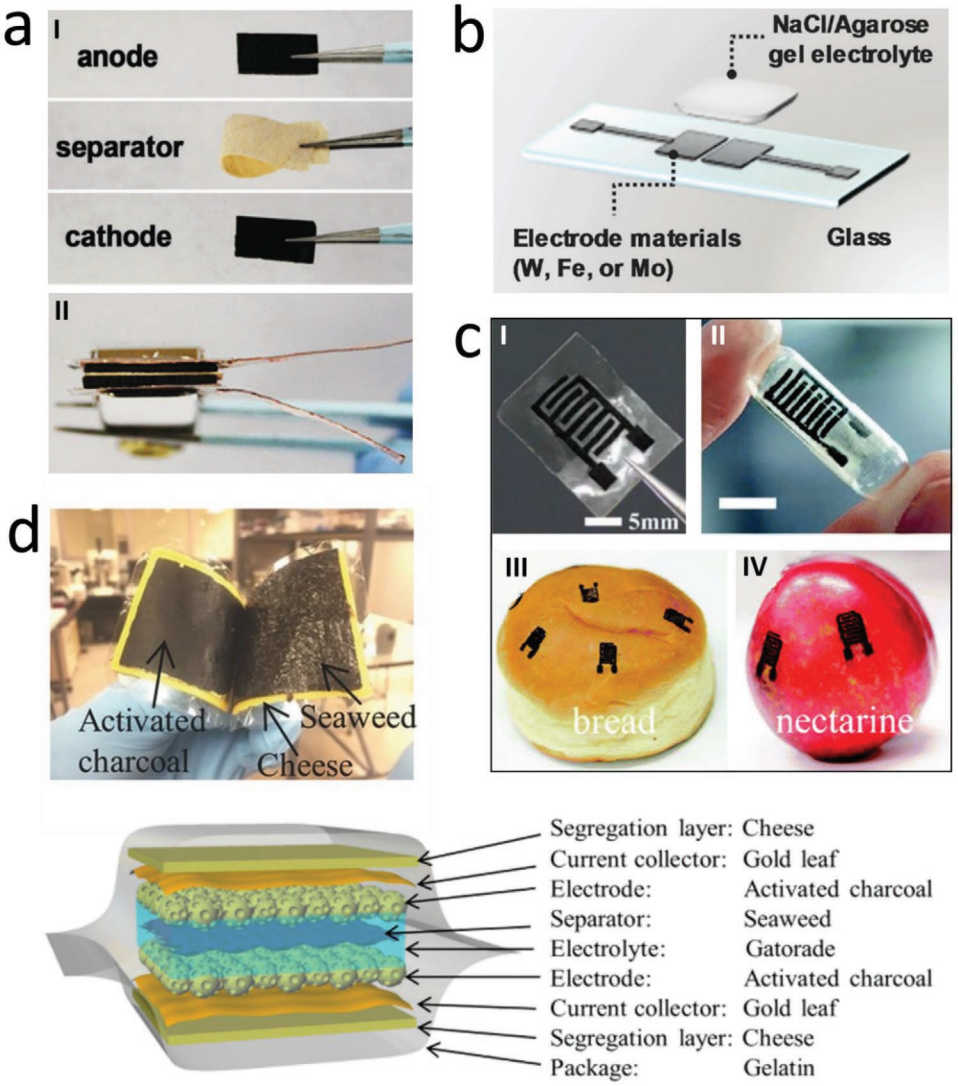

Figure 12. a) All-wood asymmetric supercapacitor. i) Photograph of carbonized wood anode, all-wood separator layer, and MnO_2-carbonized wood cathode; ii) photograph of the asymmetric supercapacitor. Adapted with permission.[283] Copyright 2017, The Royal Society of Chemistry. b) Schematic illustration of the planar supercapacitor consisting of biodegradable metal thin-film (W, Fe, or Mo) electrodes and a NaCl/Agarose gel electrolyte on a glass. Adapted with permission.[286] Copyright 2017, The Royal Society of Chemistry. c) Digital image of the supercapacitor on a gelatin substrate in self-standing configuration, or conformably adhered on standard pill and foodstuff. Adapted with permission.[104] Copyright 2020, The Royal Society of Chemistry. d) i) An open supercapacitor showing the activated charcoal electrode, seaweed separator, cheese segregation layer. ii) Illustration and materials comprising the edible supercapacitor. Adapted with permission.[70] Copyright 2016, Wiley-VCH GmbH & Co. KGaA, Weinheim.

electronics field. In 2010 carbonized *Lessonia nigrescens* seaweed was proposed as electrode material for symmetric supercapacitors, showing its operability with different aqueous electrolytes, including H_2SO_4 (E513), KOH (E525), and Na_2SO_4 (E514(i)). In particular, using 0.5 mol L^{-1} Na_2SO_4 (compatible with ingestion as long as sodium remains under ADI of 200 mg per day[284]), an output voltage of 1.6 V was achieved maintaining a stable capacitance of around 90 F g^{-1} up to 10 000 charging and discharging cycles at 1 A g^{-1}.[285]

There are examples of devices that were properly designed for the interaction with the body. Ha and co-workers[286] proposed a transient micro-supercapacitor fabricated on a PLGA flexible layer, exploiting Mo for the electrodes and NaCl enriched agarose gel as electrolyte (Figure 12b). Although FDA has approved this polymer for many medical applications, its edibility is not confirmed yet, but the library of edible materials suitable as substrates is large, giving potential fully edibility to this power supply. The device can reach an energy density of 0.14 μWh cm^{-2}, a power density of 1 mW cm^{-2} on a capacitance of 1.6 mF cm^{-2}. Three devices connected in series were also integrated with an RF energy harvesting system, demonstrating its operation powering up a standard silicon LED.

Recently supercapacitors specifically designed for ingestible applications were proposed, with the ambition to operate as power supply in the GI tract. A fully edible and foldable micro-supercapacitor able to operate in a gelatin capsule immersed in gastric fluid for 28 min has been reported.[104] The device is made of gelatin as substrate, gold leaf as current collector, activated charcoal for the electrodes, and an agar aqueous solution as electrolyte, incorporating monosodium glutamate as mobile ions provider. The edible supercapacitor was demonstrated to show an energy density of 10.86 μWh cm^{-2} and a power density of 0.78 mW cm^{-2} (Figure 12c). An even more exotic example is the food-based supercapacitor published by Jiang co-workers in 2016,[70] completely made of food commonly present in diets worldwide and reaching maximum values of specific energy and power density around 9 Wh kg^{-1} and 3200 W kg^{-1}, respectively. In detail, it comprises gold leaves as current collector, porous activated charcoal (surface area of 1400 m^2g^{-1}) as electrode, seaweed as separator layer, Gatorade drink as electrolyte and edible gelatin as device encapsulation (Figure 12d). The device shows a good stability, with a capacitance between 73 and 79 F g^{-1} stable over 1000 charge/discharge cycles (1 A g^{-1}). Its operability was tested in simulated gastric fluids, where it was able to lighting up a LED for few minutes, before starting to dissolve.

3.4.3. Fuel Cell

Fuel cells are an interesting energy storage device alternative to batteries and supercapacitors, relying on an electrochemical reaction that converts the chemical energy of the fuel in electrical energy. Fuel cells are essentially composed by three parts: an anode, a cathode and an electrolyte that works often as a proton exchange membrane (PEM). Typically, PEM fuel cells use H and O_2 as fuel. Although being a promising sustainable and green technology, applications for edible electronics are particularly complex especially for the problems correlated to the hydrogen storage, and alternatives should be considered in this framework.

For example, formic acid, used as food additive (E236) for its preservative action, has been identified as a good hydrogen storage compound. It has been proposed multiple times as fuel source in fuel cell devices.[287,288] In particular it was used in the fabrication of small fuel cells ($2 \times 2.4 \times 1.4$ cm^3) for portable applications, exploiting two gold coated titanium electrodes.[289] Although the other components are not suitable for ingestion and applications for edible electronics were not considered, this approach can be considered as a step toward a new class of safely ingestible power supplies.

Of high interest is the use of BioFuel Cells, based on the action that specific microorganisms (enzymes or microbial species) perform on a selected fuel, which often have natural origin and sometimes are edible.[290] The action of an anaerobic culture of Saccharomyces cerevisiae (often used in wine fermentation and naturally present on grapes skin) on glucose was used for the fabrication of a two chamber microbial fuel cell.[291] The device has the aim to demonstrate the use of common microorganisms for a generation of voltage potential. It shows a stable operability over two days with an output voltage of 0.39 V (over a 1 kΩ load). In the proposed cell the electrodes are made of graphite, while a not edible Nafion PEM was selected.

Biofuel cells based on the use of enzymes as catalysts are also possible. With this approach a fully edible biofuel cell was proposed embedding, in an almond scaffold, two active-charcoal/olive-oil electrodes enriched with mushroom components and apple extract for the functionalization of the bioanode and biocathode respectively (**Figure 13**).[95] The selectivity in the biocatalytic pathways of these enzymes make a separating membrane unnecessary. Output power reaches ≈300 μW cm^{-2} (on a 0.24 V open circuit voltage) with performances stable for few hours. A drawback could be represented by the use of ethanol, toxic over a certain amount, and by the production of the cancerogenic acetaldehyde as fuel waste that, however, is already produced by the liver as result of an enzymatic reaction of ethanol.

3.4.4. Energy Harvesting Technologies

As an alternative to or in combination with energy generation and storage, various energy harvesting approaches can be considered as power supplies, especially when high voltage and power output are not required. The possibility to exploit physical events, already present in the environment or specifically caused by an external source, to generate ready-to-be-used energy, is of great interest in the design of self-powered microsystems. Several energy harvester prototypes have been proposed as power supplies for medical implants or biodegradable electronics systems, some of which fully composed by edible materials. Yet, often the devices proposed are nano-generators, or harvesters that are not able to transfer a sufficient or stable power capable of ensuring the electronic system operation. For this reason they can be supported by an embedded energy storage device, preferably characterized by a rapid charge time and good life cycle, e.g., supercapacitors.

It is possible to identify several harvesting sources, which for edible and biodegradable applications typically exploit vibration

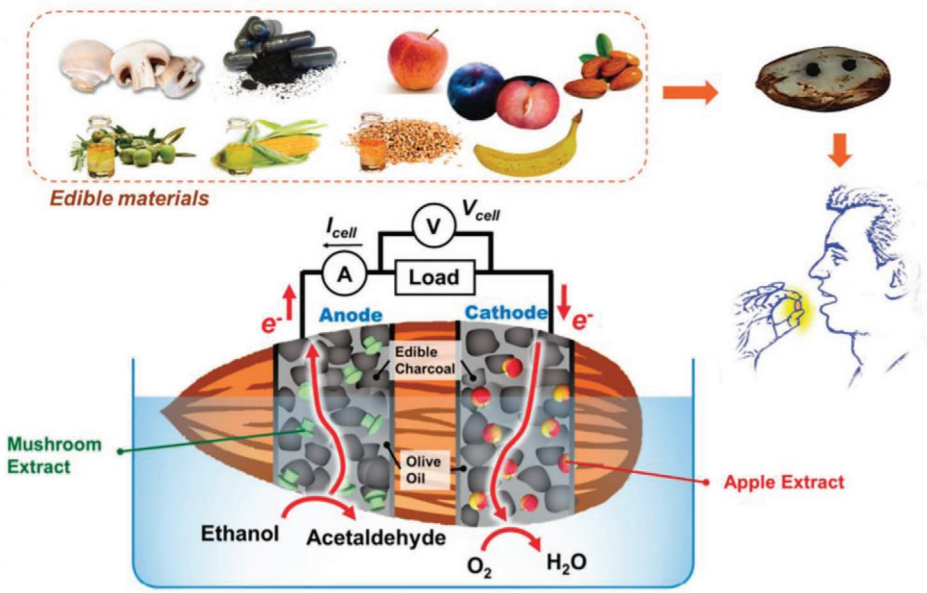

Figure 13. Fully edible biofuel cell. Top: sketches of food-based materials adopted. Bottom: Schematic architecture of the biofuel cell with reactions at anode and cathode. Adapted with permission.[95] Copyright 2018, The Royal Society of Chemistry.

or mechanical energy (e.g., triboelectric and piezoelectric effect) and electromagnetic energy (e.g., RF harvesting). In addition, chemical sources are often used for energy harvesting, as already described in the previous section. Indeed a galvanic cell exploiting gastric fluid as electrolyte or a biofuel cell that base its operation on an enzymatic reaction can be considered examples of energy harvesting.

Mechanical energy harvesting technologies, including piezoelectric and triboelectric harvesters, have been widely explored for biomedical applications, both as sensors and compact nanogenerators. In biomedical applications it is possible to take advantage from GI tract mechanical events, as peristaltic movement[47] or mastication,[292] while in food chain monitoring, vibrations, and movements at which food packaging is subjected in the transport process could be exploited.[293] Moreover, recently piezoelectric[294] and triboelectric[295] devices have been proposed as ultrasonic energy harvesters in biomedical implants. Among piezoelectric materials, the best known compound is the inorganic carcinogenic lead zirconate titanate. Despite its use encapsulated in an ingestible device,[47] edible applications have to be excluded. Among inorganic and high-performing piezoelectric material, there is the previously mentioned GRAS listed and EFSA supplement approved ZnO.[66,296,304,305] This oxide was proposed by Rogers and co-workers[297] as active material in a transient biocompatible device for energy harvesting, embedded between two magnesium electrodes, on a silk substrate (**Figure 14**a). Among FDA approved polymers, interesting results were obtained also with PLLA, which under specific processing can reach a good piezoelectric constant of ≈11 pC N^{-1}.[260] It was exploited to realize biocompatible and biodegradable pressure sensors when sandwiched between two Mo electrodes (Figure 9b), and it appears suitable also for the design of nanogenerators. PLLA was accepted by FDA for cosmetics and implants, while its edibility is not confirmed. The work is also of great interest because it demonstrates the possibility to increase the piezoelectric properties of a material by improving the polymer chain orientation degree and its crystallinity, an approach that might be considered for other edible materials showing minor piezoelectric effect. Interestingly, a piezoelectric effect can be recorded in a variety of organic and edible materials such as silk, glycine, collagen,[298] and even in bone and tendons.[299] As already reported in the section dedicated to sensors, even the integration of broccoli powder as active material in an all food based piezoelectric force sensor and microphone is possible,[96] being of inspiration for future realization of safely ingestible nanogenerators.

Mechanical energy can also be converted by means of the triboelectric effect. Given the various origins vibrations can have, development of triboelectric sensing devices is challenging and could be affected by artefacts, while exploitation of triboelectricity for nanogenerators appears a more promising option. A biodegradable triboelectric nanogenerator was proposed in 2016, consisting in a friction architecture composed by a PLGA nanostructured layer lying on a flat PLC layer, sandwiched between two Mg electrodes. The device, beside exploiting biomaterials already proposed for drugs systems, shows a good power density of 32.6 mW m^{-2} (on a 80 MΩ load resistance).[300] Much higher performances with a power density of 5 W m^{-2} (on a 80 MΩ load) have been obtained by a transient triboelectric nanogenerator in contact-separation mode, composed by PLA as active material, a nanofiber membrane and a nanostructured gelatin film, sandwiched between Mg electrodes (Figure 14b). More modest but interesting results, with a power density of 0.02 mW m^{-2} (on a 500 MΩ load resistance), were obtained with a fully edible triboelectric device exploiting common food materials, in particular: a seaweed layer as active material, edible silver leaves as electrodes and a rice sheet as substrate[301] (Figure 14c).

Another opportunity is to exploit RF harvesting, perhaps the most obvious options for edible food tagging applications,

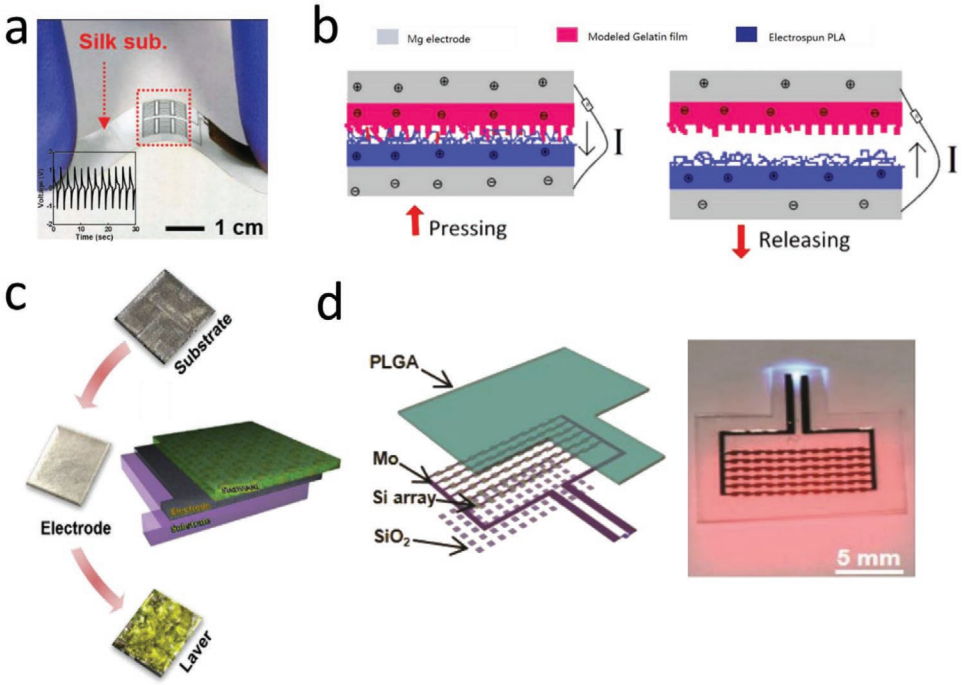

Figure 14. a) Optical micrograph of a transient ZnO energy harvester on a thin silk film, with the output voltage in the inset. Adapted with permission.[297] Copyright 2013, Wiley-VCH GmbH & Co. KGaA, Weinheim. b) Schematic structure and component of a biodegradable triboelectric generator. Adapted with permission.[306] Copyright 2017, Elsevier. c) Schematic illustration of a fully edible triboelectric device fabrication. Adapted with permission.[301] Copyright 2019, Elsevier. d) Top: rendering of the photovoltaic device components; bottom: photograph of the photovoltaic biodegradable device powering a blue LED during near infrared exposure. Adapted with permission.[305] Copyright 2018, Wiley-VCH GmbH & Co. KGaA, Weinheim.

exploiting approaches already developed for smart packaging. The required building blocks for such harvester are a suitable resonator, i.e., an antenna, and an AC/DC rectifier. The former has been already designed in multiple shapes and will be described more thoroughly in the following communication section, while the latter has not been proposed yet in an edible form, although progress in the development of fully printed diodes with conjugated active materials may suggest a starting point.[302] For applications deep into the body, practical challenges remain. Especially because of the signal attenuation through the body fluid and tissue,[303] on top of problems correlated to a precise relative orientation of the harvester and the external equipment.

Other energy harvesting approaches, such as photovoltaic (PV) and thermoelectric, have been proposed as biodegradable power supplies for biomedical or transient purposes, but remain just future perspective for edible electronics applications.

Thermoelectric devices, by virtue of converting heat flux in electrical energy, are good candidates to exploit thermal gradients at the food-environment interface, especially for products delivered through a cold chain, both for sensing and harvesting. Thermal gradients inside the body offer another possibility as well. However, edible thermoelectric generators have not been proposed yet. So far, only a platform based on a cellulose substrate and silver interconnections was suggested.[304]

The use of light as source for energy harvester can also be interesting. Recently a fully biodegradable, monocrystalline silicon PV platform, has been proposed as a near infrared energy harvester for subcutaneous medical implants.[305] The whole device lays on a PLGA layer and incorporates as active materials SiO_2, Si, along with boron and phosphorous dopants (Figure 14d). Although P and B are commonly present in food and SiO_2 is in the list of food additives (E551), the edibility has to be considered specifically for the whole system and it is not discussed in this work. Because of the difficulty in bringing light deep inside the body, plausible applications shall mainly regard devices designed for operation out of the body.

3.5. Communication Strategies

Signal transmission represents the final necessary building block that we discuss in view of a future edible system. Clearly, edible devices are not meant to be wired, and most of them intrinsically necessitates a wireless signal transmission capability. Examples of fully edible electronics systems are few and exploiting elementary architectures for the signal communication, with extremely low data throughput, if any. Indeed, the majority of fully edible systems are wireless, chip-less sensors, composed by resistor-inductor-capacitor (RLC) resonators[19,96,103] that allow to monitor variation in resistive and capacitive components of impedance-based sensors selectively sensitive to environmental or physiological parameters.

Challenges in this field are several and of enormous relevance, both in terms of requirements for a compact and edible microelectronic architecture and for the transmission robustness requirements (data quality, consistency, interoperability, and security), appearing even more complex for biomedical

applications falling within the Wireless Body Area Networks (WBAN) context, characterized by strict communication standards (e.g., IEEE 802.16.6).

In general, it is possible to take advantage from many different communication strategies. RF communication represents one of the gold standards exploited by implantable and ingestible devices, as well as by wireless electronics devices for the IoT. At present, it is unlikely to predict the soon development of fully edible systems complying with available international communication standards for high and ultra-high frequency range (Bluetooth, ZigBee, and Ant+), and devising simplified communication schemes appears as a necessity in the shorter term.

Intra body communication (IBC) presents an alternative scheme, using the human body as physical medium for the signal transmission. This approach overcomes problems related to the RF transmission through the body tissues and looks promising for edible electronics applications, both for ingested devices as well as for food industry applications, where the food itself could be used as signal propagation medium. Also sound, being a physical phenomenon able to transmit well in various media, is a candidate, with several edible piezoelectric devices already proposed.

Finally, optical approaches can play a role as well. For example, edible halochromic materials, generally used as pH indicators, are self-standing systems communicating with optical feedback, while edible OLEDs or ECDs/thermochromic pixels could be exploited in displays technologies.

In this section, the above strategies are discussed, reporting the most notable examples falling in the context of ingestible and edible electronics.

3.5.1. Radio Frequency Communication

RF is the most commonly used wireless technology in IoT context and it is also widely used in biomedical devices working in the proximity or inside the human body, often in the context of a WBAN. These networks are regulated by specific standards that can guarantee robust and safe transmission of data. The majority of ingestible devices present on the market or at the stage of human trials are designed to transmit data in the frequency range described by the IEEE 802.15.6 standard for medical devices (420–450 MHz).[20,307,308] Currently, the use of these standards for edible electronics is impractical for limitations correlated to the power and high frequency operation requested, besides the need of complex integrated circuits.

RFID technology is also widely used for signal transmission, and the implementation of passive tags appears particularly suitable for edible electronics purposes. Indeed, passive tags do not require any integration with power supplies, and in addition near field-communication modules operating at 13.56 MHz are cheap and commonly integrated in electronics devices, simplifying the reading procedure.

Fully edible RFIDs do not exist yet, but FDA recently reviewed the premarket notification (510(k)) of an RF ingestible system for medication adherence assessment, which degrades within the GI tract, and approved it as safe and effective medical device.[12,258,309] The system includes an ingestible event marker, based on an hybrid structure exploiting a proprietary technology (eBurst) to transmit digital messages to and from the ingestible sensor by means of an RF-tag powered by a primary cell (AgCl-Mg) starting its electrochemical reaction in contact with the gastrointestinal fluids (Figure 9e).

Fully edible communication strategies proposed until now consist of chipless RF tags embedding impedance-based sensors, as those reported in the previous sections. The sensor has the role to alter the resonance frequency of the circuit that can be then wirelessly monitored.

For example, the signal transmission for the food-conservation-status sensor described in Section 3.3.1 relies on a sub-micrometric thin gold coil fabricated on a silk substrate. Different fabrication procedures, such as inkjet printing, physical evaporation and silk transfer applied micropatterning, have been exploited, and different geometries operating among the MHz, GHz, and THz regimes were tested[19] (Figure 10a). The same communication strategy is used to communicate pH and pressure values sensed by the capacitive sensors described in Section 3.3.1 and shown in Figure 10a,d by means of gold and zinc/iron resonators respectively.[96,261] Finally, remarkable is also the smart solution adopted by Bao and co-workers for the design of an Mg based double coil resonator laying on a PLLA substrate. The antenna is fabricated through a simple plotting procedure performed with a computer-controlled laser cutter, and it is then integrated with an arterial pulse sensor, already described in Section 3.3.1.[103]

3.5.2. Intra Body Communication

IBC exploits the human body as a transmission medium and can be considered a promising option for devices operating within the GI tract. It was introduced for the first time at the end of the last century,[310] as a communication strategy for electronic devices in direct contact with the body, or in close proximity, to exchange digital information though the biological tissues. In particular, it was initially proposed for personal area networks, for example as a strategy to exchange electronic cards information by shaking hands.[310] Later IBC was proposed as a communication strategy also for implantable medical devices, with several advantages. Indeed, IBC is characterized by an intrinsic high security level, necessarily requiring the direct skin contact of the reader. It is characterized by a higher energy efficiency with respect to RF communication strategies falling in the IEEE standards[311] and it also allows lower frequency operation, down to a range not viable with RF for ingestible devices because of the resonators dimensions. Moreover, compared to other wireless technologies, a precise orientation and position of the external reader is less relevant. The main constraint is to operate in a low enough frequency domain to avoid interfering with other medical devices or to avoid inducing local overheat, but at the same time at frequencies higher than physiological ones. The resulting suitable frequency spectrum ranges from kHz to few MHz.[312] For example, IBC operates with the standard IEEE 802.15.6 for WBAN with a dedicated band centered at 21 MHz.[311,313]

To date, edible systems exploiting it have not been reported, while IBC communication strategy based on galvanic coupling

has been adopted in the previously cited digital medicine system Abilify MyCite developed by Otsuka Pharmaceutical Co., Ltd. and Proteus Digital Health. The device is composed by an ingestible event marker approved by FDA in 2017[11] and its working principle was presented in 2015, along with promising results of in vivo tests. The system embeds an Mg/CuCl primary cell that is activated when in contact with gastric fluids. The energy supplied is sufficient to generate an electric field that propagates in the surrounding tissues and can be detected by a noninvasive external patch placed over the abdomen. The battery also supplies power to a small CMOS circuit, which modulates the electrical field communicating to the user the dose and the medication specifics through a unique and private digital code. Data are transmitted with frequency between 10 and 30 kHz with a rate of two packets for second (Figure 9d). Transmission performances change in relation to the patient body mass index, and in this specific case the signal remains above the readable threshold of 1 μV up to body mass index of 56.8 kg m^{-2}.

3.5.3. Acoustic and Ultrasounds Communication

Sound and ultrasound waves represent another communication strategy that can be exploited for edible electronics.

In the medical field, ultrasounds have been used for long time for imaging, exploiting waves generated by an external source, which also records their reflection. More recently, ultrasounds have been also used as an effective method to control drug release, thanks to both their thermal and mechanical effects.[314] Ultrasounds have been proposed also as a bidirectional communication strategy that consist in implants able to operate as ultrasound receivers and transmitters. Performances and applicability of this technology are still not comparable to well established approaches as RF, but in the framework of edible electronics it may be considered as a plausible path toward an ultrasonic intra-body network, especially considering the ultrasounds safety also over long exposure and their low signal attenuation through the body.[315]

The use of the acoustic range offers instead a mean to provide an audible informative feedback for edible electronics designed for operation out of the body.

Reports on edible piezoelectric materials are numerous,[96,260,297,299] and some of them have shown good sensibility to mechanical waves, demonstrating their operability both as microphones (receivers) and speakers (transmitters).

As already reported, a piezoelectric device based on an edible compound of broccoli and gelatin, sandwiched between two gold layers, was proposed, and its operability as a good fidelity microphone was tested by recording the loudspeaker diaphragm vibration in a frequency range between 27 and 131 Hz (**Figure 15**a). More recently an edible piezoelectric device, based on a β-chitin film and silver electrodes, was used as an acoustic actuator, able to generate sound waves in the 300–20 000 Hz range, detectable by a standard microphone (Figure 15b). The same device was proposed as a microphone, showing good performances, and taste for good music, recording "Paganini Caprice no. 24."

3.5.4. Optical Strategies

An alternative to build a communication strategy is to take advantage from the optical properties of certain materials and devices. The very same halochromic materials reported in pH sensors in Section 3.2.4 are inherently providing a visual feedback, without the support of any circuitry. Where more complex sensing circuits are possible, pixel and displays based on edible OLED and electrochromic technologies could be beneficial for food and drugs tagging.[199,245]

Also passive technologies, not strictly connected to electronics, can be considered. Recently, a very interesting example of an anti-counterfeiting optical tag based on food and drugs cryptography was proposed. The device is 7×7 mm^2 large and 150 μm thick, it contains a physically unclonable function, obtained by casting a mixture of fluorescent functionalized silk microparticles encapsulated by a white silk fibroin coating. The fluorescent proteins distribute themselves in a stochastic way on the tag, generating a distinct response used to extract univocal digitized keys (Figure 15c). Such code can be acquired by a smartphone camera before administration,[316] providing an unclonable information, characterized by a high security level.

Quick response (QR) code is another approach always connected to edible smart tagging and identification coding. This technology allows the fabrication of informative tags, capable of storing up to 7089 numeric characters in the 40-L version.[317] In this context, QR-codes have been inkjet printed using edible materials or specific drugs as inks,[318] both for smart labeling or antifraud purposes (Figure 15d). The tag itself is a static data storage that cannot be modified unless a hybridization with other technologies (e.g., electrochromic displays) is implemented.

4. Summary and Outlook

Edible electronics is in its infancy, with exciting opportunities going hand in hand with formidable challenges an emerging field has to face. In this progress report we collected the main ideas, perspectives, useful findings, and advancements that have been achieved in the field in the recent past. We foresee that its interdisciplinary character, albeit a hurdle in the beginning, will soon turn into an asset, fostering synergy within a broad scientific community.

According to our vision, the ideas of green and ingestible technologies, unified under the dome of information technology, material and medical sciences, gave the rise to the sprouting of edible electronics seeds. The emerging sustainable edible electronics platform (**Figure 16**) aims to overcome limitations of the currently available technologies by envisioning an unconventional electronic functional system safe for human ingestion and of no harm to the environment. Therefore, this field has the potential to disruptively impact fundamental areas of life and to enhance individual and social health and wealth. Food, pharmaceutics, and biomedical industries are among the beneficiaries. Exploiting digestible materials as building components, edible electronics offers a natural solution to a number of issues in clinical medicine and food technology, all related to contamination of the natural environment, being it a human

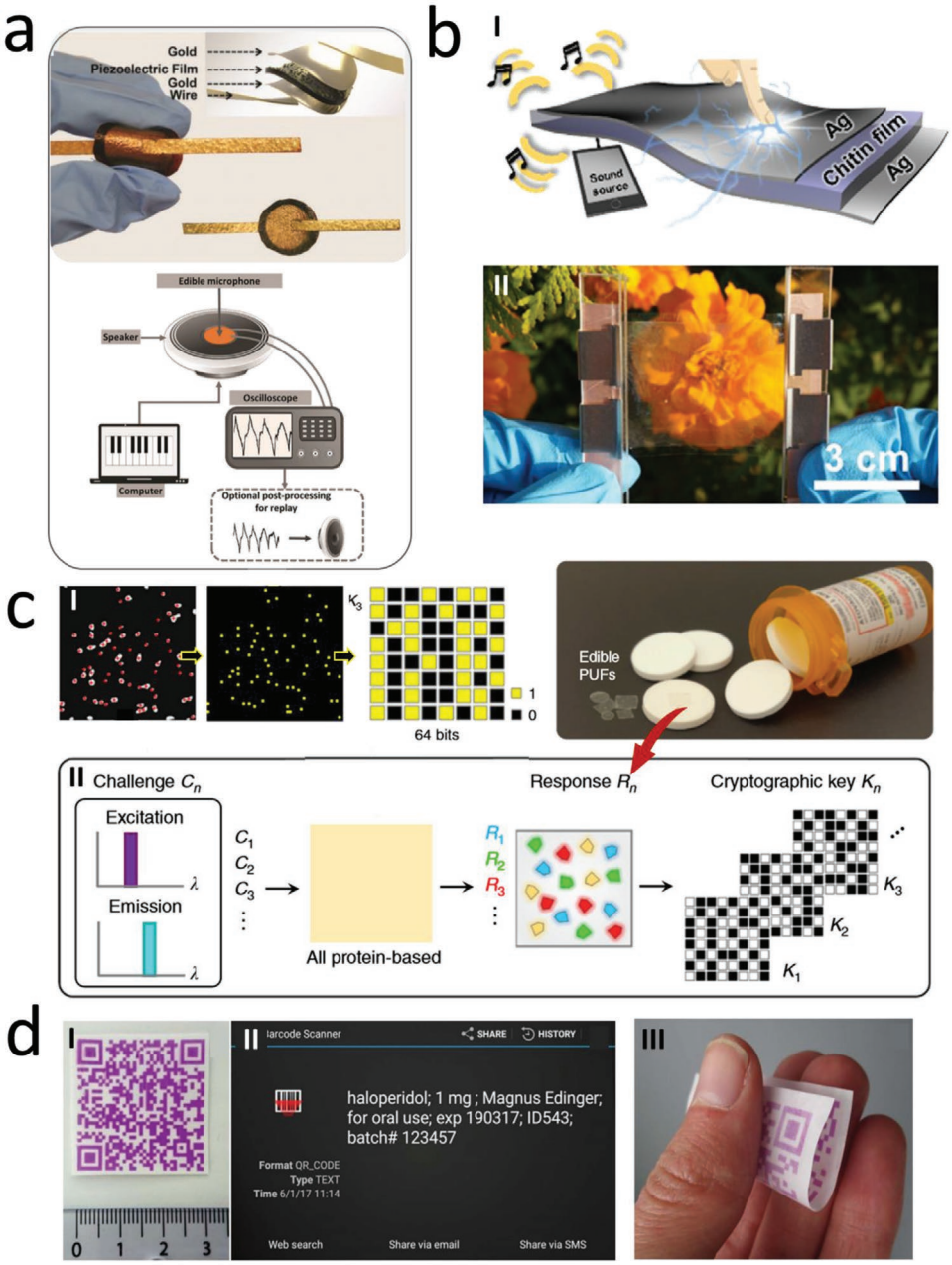

Figure 15. a) Top: photograph of a piezoelectric speaker based on broccoli compound sandwiched between two gold layers; bottom: setup used to analyze the acoustic signal. Adapted with permission.[96] Copyright 2017, Wiley-VCH GmbH & Co. KGaA, Weinheim. b) Top: rendering of a chitin based piezoelectric device; bottom: photograph of the piezoelectric device. Adapted with permission.[319] Copyright 2018, Elsevier. c) Anti-counterfeiting optical tag based on food and drugs cryptography. i) fluorescent silk microparticles pattern identification and information binarization; ii) process flow for authentication. Adapted with permission.[316] Copyright 2020, Springer Nature. d) i) An edible optical QR code. ii) the screen-shot from a mobile phone, using the Barcode Scanner. iii) photograph of the printed dosage tag when folded. Adapted with permission.[318] Copyright 2017, Elsevier.

body or a waste ground. The approach will solve the retention problem, common for many ingestible devices, and eliminate the need of their recollection, countering at the same time the waste problems related to smart food packaging by making the food smart and informative by itself. In perspective, edible electronics is also expected to find synergies with soft-robotics, allowing for example to integrate sensors and control with edible actuators toward biodegradable and edible robots.[320]

The review work includes the coordinated assembling of edible materials, classified by electronic properties, in the comprehensive "library" that is to be widely expanded with advances in the field. The scope of materials potentially suitable for edible electronics extends from commonly ingested foods, drugs and food additives, among which are essential nutrients and vitamins, to compounds not yet defined as edible by the authorities, but derived from such (e.g., PLA, PLGA, ecoFlex)

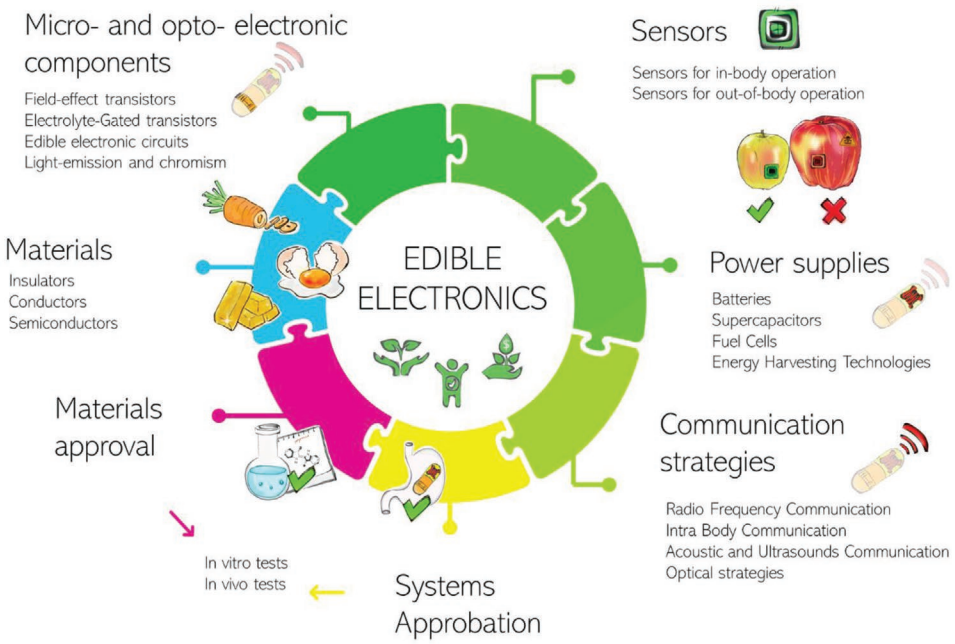

Figure 16. Schematic conceptual diagram of the edible electronics vision. The diagram represents the feature steps along the challenging path of realization and integration of edible electronic systems: starting from edible materials selection, their approval and adoption as electronics constituents (insulators, conductors, semiconductors) to the development of the edible electronics components (micro and optoelectronic components, sensors, power supplies, communication strategies), composing the final targeted system anticipating approbation.

or often used in contact with the body or food (e.g., perylene diimide, vat yellow 1, vat orange 3). The most notable edible or partially edible electronic devices and systems, reported to date, embedding these materials, have been discussed. The reviewed examples prove the feasibility of rather exotic devices, challenging common thinking: transistors based on carrot pigment, vitamin B OLEDs and curcumin electrochromic displays, silk sensors, power supplies exploiting soft drinks and cheese, microphones built from broccoli and gelatin, magnesium conductive coils or chitin based speakers for wireless signal communication, among others.

Specific challenges arise depending on the required system functionalities, starting from materials selection to the development of the components of the final targeted system. From the material selection point of view, an approach is to find within materials that are intrinsically edible (approved by FDA), those that exhibit adequate electronic properties and suitable processing capability. Materials with suitable electronic and processing properties, but which are not yet approved for ingestion, will clearly have to be validated by competent organs, as well as the final components and systems integrating them. In vitro toxicity texts with improved predictive capabilities are desirable in this context. Restrictions on the operation power of the edible device should be as well considered in order to eliminate any risk to the consumer/patient's safety. Apart from that, challenges occur in the sector of communication strategies as integration of edible electronics in the everyday life requests higher standards in terms of data quality, throughput and security. Biomedical in-body applications reveal an even more complex framework where, beside the stricter requirements, the signal propagation occurs in a medium with significant losses. The unique combination of functionality, sustainable processability, robustness, and complete safety of the materials is not straightforward, but mandatory for managing an edible electronics platform addressed to become a part of our daily life. In this context, challenges related to the ethical standards are critical, and should be faced straightaway by the time the technology get "wiser."

The mission to strengthen public acceptance promoting edible electronics as a transparent and regulated field is fundamental yet not trivial. The society could easily accept and take advantage from new technologies completely composed by common food ingredients present in an ordinary diet, while being more reluctant toward safe artificial and functionalized materials.

Owing to the numerous challenges, the progress in this appealing field appears to be relatively slow. Yet, edible electronics opens great long-term perspectives and provides a framework for consolidating diverse knowledge. With primary benefits in terms of technological impact, it can profoundly expand the scope to social, environmental, economic, and industrial sectors by offering new unconventional materials, devices, approaches and processes. Additionally, the "ad hoc" protocols regulating the field and elaborated in coordination with the relevant regulation bodies will be essential for monitoring and quality control within the marketplace. Edibility assessment protocols will be as well fundamental as a way to broaden the materials library and boost the improvement of electronic performances, while guaranteeing high safety levels. To conclude, combining imagination and creativity with multidisciplinary knowledge is the key factor for successful development of a novel edible technology that seemed to be too ambitious until now.

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Conflict of Interest

The authors declare no conflict of interest.

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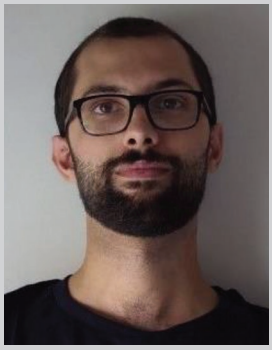

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