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Food-Based Edible and Nutritive Electronics

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A new class of electronic materials derived predominantly from natural foods and foodstuffs, with minimal levels of inorganic materials, is developed and studied to build edible electronic components and devices compatible with the gastrointestinal (GI) tract. A "toolkit" of food-based electronic materials, fabrication schemes, basic device components, and functional devices with integrated sensing and wireless signal transmission is reported. These new materials establish the possibility to extend GI electronic devices beyond the ingested nondegradable systems to edible and nutritive systems, in which the described materials may be ingested and assimilated as metabolized nutrients. This study represents a new era of edible electronics with the potential to revolutionize modern biomedical technologies and devices.

On-person electronics, as either wearable or implantable systems, have an increasingly significant role in healthcare monitoring, diagnosis, and therapy.[1–4] Progress in health-related device development has been facilitated by dramatic advances in electronic materials – with expansion of the form factor and constituents of electronic materials, with the advent of flexible,[5] stretchable,[6–13] and transient[14,15] systems. Beyond skin-based systems, with the shortcoming of limited variable detection – such as heart rate,[16] temperature[17] or sweat-based body constituents,[18] or implantable systems, which while robust remain invasive, with the risk of infection bleeding and the need for surgical recovery with malfunction, a body domain that has only been partially explored as an electronics locale has been the gastrointestinal (GI) tract. The GI tract is a primary interface between the external environment and the internal milieu, affording tremendous surface area for device residence and monitoring of a wide range of health and disease states and conditions.[19] To date, a limited number of devices have been fabricated for GI use – which may be categorized as indigestible – either swallowed whole or implanted via endoscopy,[20,21] which typically traverse the gut intact and are then eliminated. Edible, digestible, and absorbable devices would further advance the field, though requiring advances in materials, beyond initial efforts.[22–27] Here, we provide an advancement in electronic material development with the identification and formulation of a "toolkit" of electronic materials and components made largely of natural foods and foodstuffs, with minimal levels of inorganic materials utilized to fill identified functional requirement gaps and to build electronics. We advance herein both edible and nutritive electronic materials, in which the described materials may be ingested and assimilated as metabolized nutrients.

In the present study, we began with natural foods and foodstuffs as candidates for electronics materials and then based on specification requirements identified additional edible processed foods, food components, and on a limited basis nontoxic levels of electronic materials, to create full electronic constructs. The best candidates from natural, processed, and adduct food materials were then selected to create our "preferred food kit" for component fabrication. Specific individual and combined components were built and characterized utilizing the preferred food kit. Finally, several active systems, i.e., systems with specific functionalities, including a pH sensor, a radio frequency filter, and a microphone, were constructed and tested. The present study significantly enables edible electronics with the potential to advance an emerging domain of biomedical technologies and devices.

As a first step, reference materials were selected to establish the specifications needed for components. An electrical circuit

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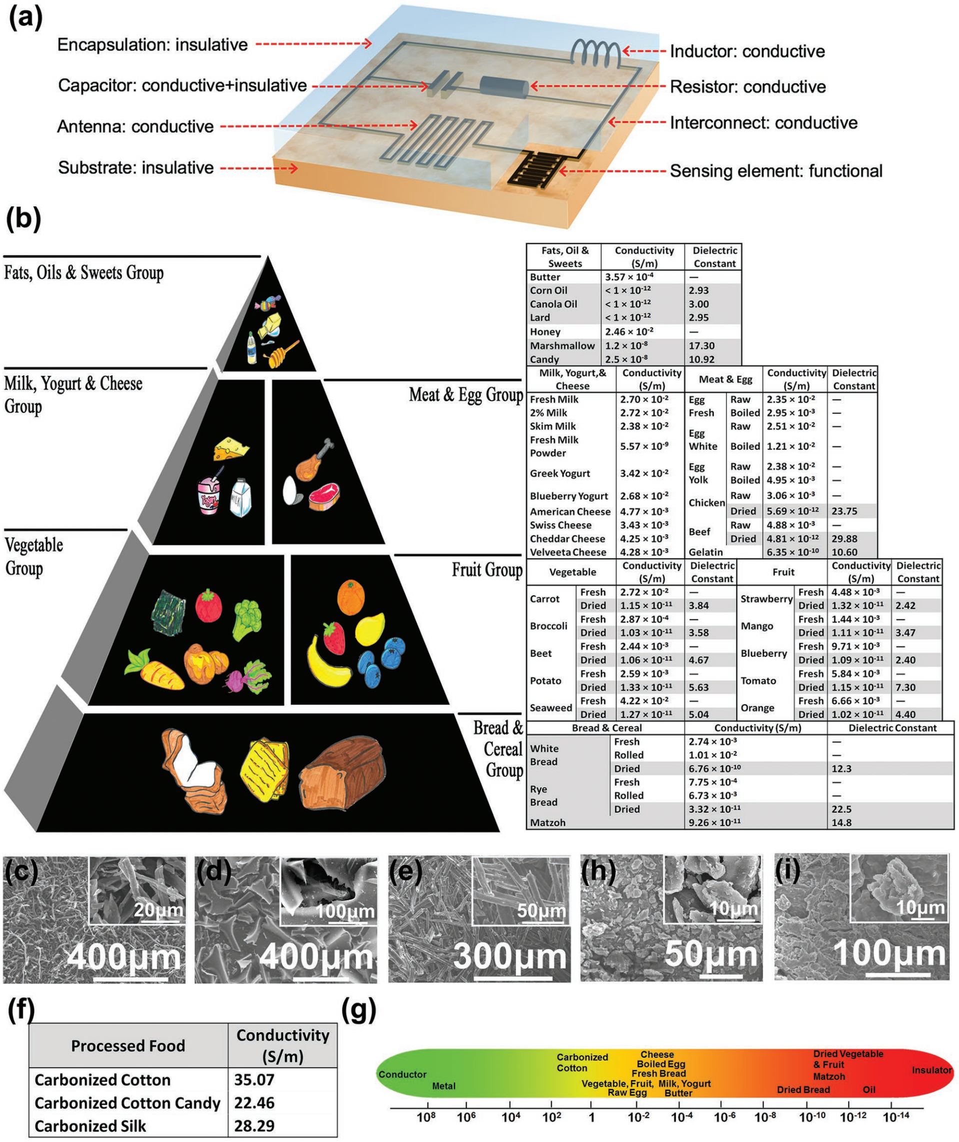

Fats, Oil & Sweets	Conductivity (S/m)	Dielectric Constant
Butter	3.57×10^{-4}	—
Corn Oil	$< 1 \times 10^{-12}$	2.93
Canola Oil	$< 1 \times 10^{-12}$	3.00
Lard	$< 1 \times 10^{-12}$	2.95
Honey	2.46×10^{-2}	—
Marshmallow	1.2×10^{-8}	17.30
Candy	2.5×10^{-8}	10.92

Milk, Yogurt,& Cheese	Conductivity (S/m)
Fresh Milk	2.70×10^{-2}
2% Milk	2.72×10^{-2}
Skim Milk	2.38×10^{-2}
Fresh Milk Powder	5.57×10^{-9}
Greek Yogurt	3.42×10^{-2}
Blueberry Yogurt	2.68×10^{-2}
American Cheese	4.77×10^{-3}
Swiss Cheese	3.43×10^{-3}
Cheddar Cheese	4.25×10^{-3}
Velveeta Cheese	4.28×10^{-3}

Meat & Egg		Conductivity (S/m)	Dielectric Constant
Egg Fresh	Raw	2.35×10^{-2}	—
	Boiled	2.95×10^{-3}	—
Egg White	Raw	2.51×10^{-2}	—
	Boiled	1.21×10^{-2}	—
Egg Yolk	Raw	2.38×10^{-2}	—
	Boiled	4.95×10^{-3}	—
Chicken	Raw	3.06×10^{-3}	—
	Dried	5.69×10^{-12}	23.75
Beef	Raw	4.88×10^{-3}	—
	Dried	4.81×10^{-12}	29.88
Gelatin		6.35×10^{-10}	10.60

Vegetable		Conductivity (S/m)	Dielectric Constant
Carrot	Fresh	2.72×10^{-2}	—
	Dried	1.15×10^{-11}	3.84
Broccoli	Fresh	2.87×10^{-4}	—
	Dried	1.03×10^{-11}	3.58
Beet	Fresh	2.44×10^{-3}	—
	Dried	1.06×10^{-11}	4.67
Potato	Fresh	2.59×10^{-3}	—
	Dried	1.33×10^{-11}	5.63
Seaweed	Fresh	4.22×10^{-2}	—
	Dried	1.27×10^{-11}	5.04

Fruit		Conductivity (S/m)	Dielectric Constant
Strawberry	Fresh	4.48×10^{-3}	—
	Dried	1.32×10^{-11}	2.42
Mango	Fresh	1.44×10^{-3}	—
	Dried	1.11×10^{-11}	3.47
Blueberry	Fresh	9.71×10^{-3}	—
	Dried	1.09×10^{-11}	2.40
Tomato	Fresh	5.84×10^{-3}	—
	Dried	1.15×10^{-11}	7.30
Orange	Fresh	6.66×10^{-3}	—
	Dried	1.02×10^{-11}	4.40

Bread & Cereal		Conductivity (S/m)	Dielectric Constant
White Bread	Fresh	2.74×10^{-3}	—
	Rolled	1.01×10^{-2}	—
	Dried	6.76×10^{-10}	12.3
Rye Bread	Fresh	7.75×10^{-4}	—
	Rolled	6.73×10^{-3}	—
	Dried	3.32×10^{-11}	22.5
Matzoh		9.26×10^{-11}	14.8

Processed Food	Conductivity (S/m)
Carbonized Cotton	35.07
Carbonized Cotton Candy	22.46
Carbonized Silk	28.29

Figure 1. Selections and characterizations of food-based materials as per their electrical properties. a) An illustration showing necessary components in a typical electrical circuit with specific characteristics, which guides the search of food-based materials for edible electronics. b) A typical food pyramid with conductivities and dielectric constants of some representative food materials according to recognized food groups. The shaded elements represent food materials that can provide required conductivities as insulators/dielectric materials. c–e) Scanning electron microscopy (SEM) images for carbonized cotton, cotton candy, and silk, respectively. f) Conductivity of processed food materials. g) Conductivity spectrum of food-based materials that can cover a wide range of electrical conductivity from conductors to insulators. h,i) SEM images for broccoli powder and the cross-sectional view of the edible piezoelectric thin film consisting of gelatin and broccoli powder.

usually consists of the following components as illustrated in **Figure 1**a, including resistors, capacitors, inductors, and antennas that are connected via interconnects and supported by a substrate and encapsulated by an encapsulating layer. These components require insulators and conductors, which can be specified by their electrical conductivities. For insulators (or dielectric materials), the conductivity σ needs to be $<10^{-8}$ S m^{-1}; while needing $>10^{6}$ S m^{-1} for conductors.[28] Insulators are utilized for encapsulation and as the dielectric materials in capacitors, with the capacitance typically in the range of 1 pF–100 nF.[29] Conductors appear in wires/interconnects, electrodes, and other components. Mixed insulators and conductors may be utilized to build resistors, with a wide range of resistance from 10 Ω–20 MΩ.[29] These reference values establish the specifications needed for components and device fabrications using food materials. Moreover, functional devices are indispensable to build sensors and their characteristics are defined by specified applications.

As a second step, specific natural, unprocessed foods were selected, organized according to recognized, defined nutritional food groups from the Food Guide Pyramid (e.g., cereals, meat, vegetables, bread, fats, etc.), as candidate materials for analysis due to their electrical properties and subsequent component or device fabrication. Conductivity probes and semiconductor parameter analyzer were utilized to perform the characterizations (see details in the Supporting Information). As seen in Figure 1b, for electronic conductivities, oils and dried foods (including meat, vegetables, gelatin, fruits, and bread) that are shaded achieve the required conductivities as insulators/dielectric materials. Here, gelatin was cataloged as meat, as it is derived from collagen in animal raw materials. Dried foods were prepared using a pneumatic convection food dryer (see the Supporting Information). The reason these are good insulators is that these foods do not contain mobile carriers to conduct electric current. On the contrary, foods with significant salts (e.g., butter) and/or water content (e.g., fresh meat and vegetables) are relatively conductive due to the presence of free ions for electric current conduction. A more comprehensive list of electrical conductivity and dielectric constants of commonly accessible food materials are provided in Table S1 (Supporting Information). Figure 1b demonstrates that natural foods largely afford good insulators/dielectric materials, but are poor conductors for electrical components.

In order to fill the gap in conductivity to create full constructs in electronic components, as a third step, processed food stuffs and nontoxic levels of electronic materials were similarly identified and analyzed. In addition to edible metals as conductors, carbon derived from processed foods, basically activated charcoal, carbonized sugar (cotton candy), cellulous (cotton), and protein (silk) were selected and tested. An annealing process was utilized for carbonization (see the Supporting Information). Energy dispersive X-ray spectrometry results reveal that they (all materials annealed) are largely carbon (see Figure S1 in the Supporting Information). Different microscale morphologies of carbonized cotton (Figure 1c), cotton candy (Figure 1d), and silk (Figure 1e) as observed via scanning electron microscopy (SEM) images, attribute to different electrical properties. Specifically, the fiber-like carbonized cotton tends to form a continuous path to conduct electrons, while the flake-like carbonized cotton candy and silk require aggregation to form the similar conductive path. Electrical conductivity results given in Figure 1f show that these processed food materials and nontoxic metals (Table S2, Supporting Information) can serve as the conductive materials. It is apparent from Figure 1b–f and Table S2 (Supporting Information) that edible food materials can cover a wide range of electrical conductivity as shown in the conductivity spectrum in Figure 1g. To build a conductive wire/interconnect, edible metals are good choices, while dried vegetables mixed with bread/flour and oil are good candidates for insulators. The mixed carbonized cotton candy and flour can be used to build resistors.

As mentioned in Figure 1a, in addition to insulators and conductors in electrical components, other functional materials are also indispensable, particularly for sensing. For example, piezoelectric materials can generate electricity upon mechanical stress and have been utilized in many applications including pressure sensors, microphones, and speakers. Many natural and edible materials have piezoelectric properties, such as bones and tendons.[30–32] Cellulose, which is abundant in many vegetables, i.e., broccoli and brussels sprouts, also possesses piezoelectric properties, mechanistically due to the fact that oriented cellulose crystallites exhibit shear piezoelectricity as a result of internal rotation of polar atomic groups associated with asymmetric carbon atoms.[33] Here, we utilized broccoli powder with radius less than 90 µm mixed with gelatin to form a piezoelectric composite. SEM images show the broccoli powder (Figure 1h) and a cross-sectional view of the edible piezoelectric thin film (Figure 1i). Broccoli powders (Holistic Herbal Solutions, LLC) were sieved through a sieve (mesh size 90 µm) and then uniformly mixed with gelatin solution through magnetic stirring followed by casting at 24 °C. The stiffness of the thin film was adjusted via the addition of the edible plasticizer glycerol (see the Supporting Information). The piezoelectric coupling coefficients of the edible piezoelectric thin film were characterized by using an electric shaker, accelerometer, and signal analyzer (see the Supporting Information). Coupling coefficients of the edible piezoelectric film consisting of broccoli and gelatin were found to be $d_{33} = 4.3$ pC N^{-1}, and $d_{31} = 0.31$ pC N^{-1}. These values are comparable to 5 pC N^{-1} of ZnO,[34,35] a recognized piezoelectric material. In addition to broccoli that is rich in cellulous, other cellulous-rich foods, including brussels sprouts and cabbage were also mixed with gelatin to form piezoelectric composites using a similar approach. The same characterization approach was employed and the results are provided in the Supporting Information. It is concluded that all constructs tested exhibit appreciable piezoelectric effects (Table S3, Supporting Information). Under the same weight ratio (1 g cellulous-containing vegetable to 2 g gelatin), broccoli has the strongest piezoelectric effects, correlating with the highest cellulous content.[36] It should be noted that gelatin also has detectable piezoelectric properties, however its d_{33} is more than 20 times less than that of broccoli (see the Supporting Information).

Establishment of defined electrical properties for the studied food materials afforded opportunity to build a toolkit for fabrication of a range of necessary electrical components. The best candidates from natural, processed, and adduct food materials were then selected to create our "preferred food tool kit" for component fabrication, as shown in **Table 1**. The food materials in the toolkit are grouped based upon structural and electrical functions. Insulative food materials, such as sweet potato starch, sugar powder, and flour, basically provide structural functions. Distinct applications of these materials in electrical components attribute to their different mechanical properties (e.g., elastic modulus and bending rigidity) of which

Table 1. Food-based material toolkit utilized for fabrication of electrical components.

Component	Food kit materials	
	Structural function	Electrical function
Wire	Rice paper/sugar powder/flour/rice	Gold leaf/edible metal: gold
Resistor	Sweet potato powder/flour/candy/dried fruit/vegetable	Active charcoal/carbonized cotton fiber/cotton candy/silk gold leaf
Inductor	Sweet potato powder/flour/candy/dried fruit/vegetable	Active charcoal/carbonized cotton fiber/cotton candy/silk gold leaf
Capacitor	Gelatin/dried fruit/vegetable	Gold leaf/edible metal: gold
Antenna	Sugar powder/flour/rice paper/candy/marshmallow, egg white	Edible metal: gold/gold leaf/active charcoal/carbonized cotton/silk

their characterization approach and mechanical properties are detailed in the Supporting Information. Specifically, rice paper being thin and very flexible was utilized as the substrate for wires/interconnects. Sweet potato starch and wheat flour were found to be suitable substrate materials for resistors and inductors, though dough of sweet potato starch was readily shaped without the tendency to fracture in the dried state, compared with regular flour. Sweet potato starch has a higher starch content than flour, and starch will gelatinize in the presence of water and heat. After gelatinization, starch dough becomes uniform and sticky, which makes it allowing formation of a range of shapes with a smooth surface. Thus, sweet potato starch was a preferred substrate for resistors and inductors. Conductive food materials, such as edible metals and carbonized cotton candy, contribute to the electrical functions. Wires/interconnects need to have very low electrical resistance and were largely fabricated with edible metals; while for resistors, carbonized cotton and cotton candy that have relatively low electrical conductivity were utilized. To achieve a good adhesive between the substrate and conductive regions, egg white was employed as a binding material, if necessary. Hydrogen bonding and ionic interactions with proteins attribute high adhesive strength of egg white.[37]

Specific components were then built and tested utilizing the preferred food kit as in Table 1. Optical microscopy and SEM images, along with the characterization results, are shown in **Figure 2**. The detailed fabrication approaches and characterizations are in the Supporting Information with a brief description herein. Edible wires were made of rice paper as the substrate and sputtered gold (Au) as the functional part. The thickness of the Au is of the order of 100 nm (Figure 2a). Resistors and inductors are all made of sweet potato starch and carbonized cotton candy or cotton through an extrusion process using a syringe, where the resistors are straight wires (or basically conductive "noodles") and the inductors were wound utilizing a

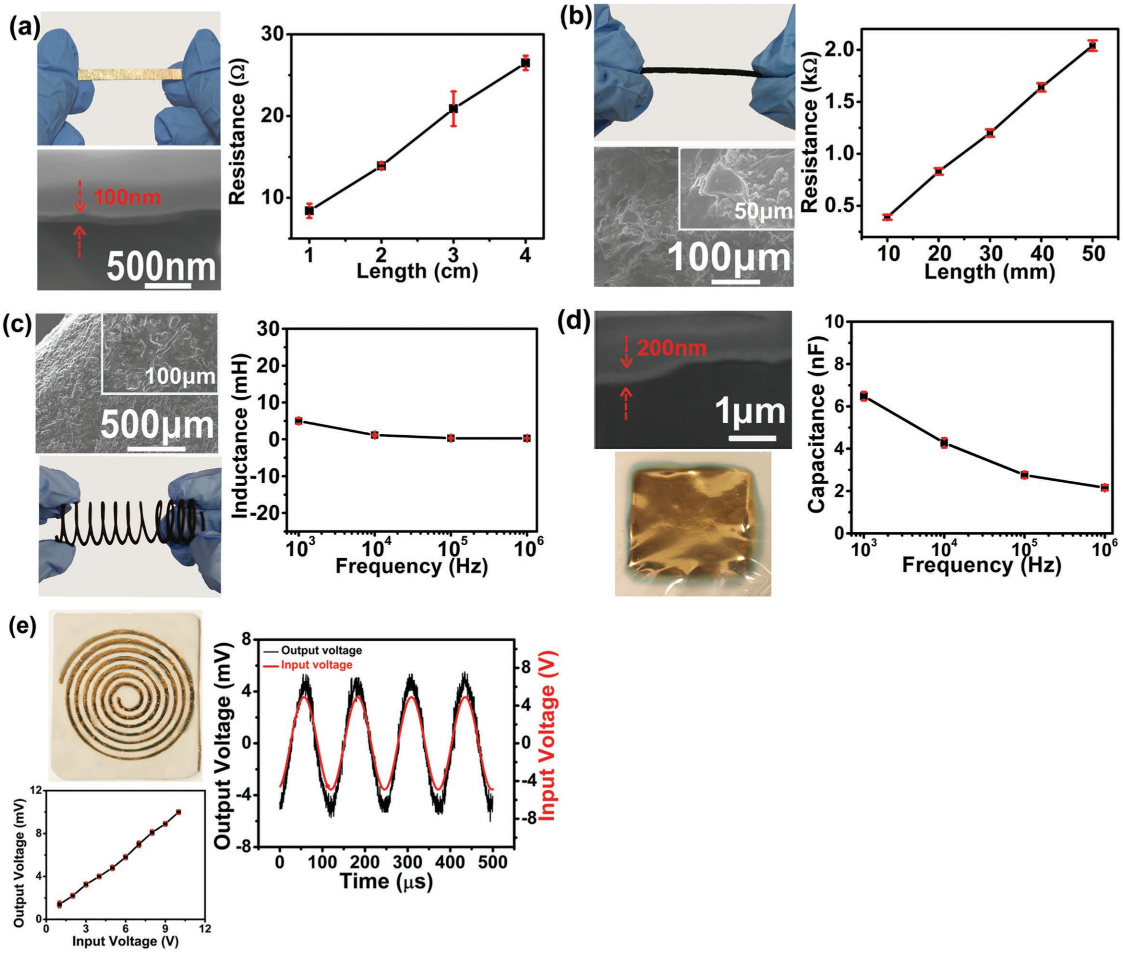

Figure 2. Results of food-based electrical components. Optical and SEM images are shown, along with the characteristics of the components. a) A wire/interconnect consisting of rice paper as the substrate and deposited Au as the conductive trace. Au layer is 100 nm in thickness. b) A resistor consisting of sweet potato starch and carbonized cotton candy. The representative value of typical resistors in conventional electronics ranges from 10 Ω to 20 MΩ.[30] c) An inductor consisting of sweet potato starch and carbonized cotton. The inductance of typical inductors in conventional electronics is in the range of 1 μH to 10 H.[30] d) A capacitor consisting of a thin layer of gelatin as the dielectric material and Au as the electrodes. The Au layer is 200 nm in thickness. The representative value of typical capacitors in conventional electronics ranges from 1 pF to 100 nF.[30] e) An antenna made of Au trace with 200 nm in thickness deposited on sugar paste as the substrate. The antenna is placed facing a 50-turn copper coil connected to a signal generator that outputs an alternating current with peak-to-peak voltages from 1 to 10 V. The antenna is connected to an oscilloscope where the signal waveforms and peak-to-peak values are recorded and shown here. The details are provided in the Supporting Information.

cylindrical core, forming a noddle-based spring configuration. An additional layer of carbonized cotton candy was added to the outside of the noodles while they are still wet to increase the conductivity. As shown in the SEM images in Figure 2b, carbonized cotton candy forms a continuous path in the noodles. The capacitors were made of thin gelatin sheets as the dielectric layers coated with edible Au as the electrodes. The thickness of the gelatin is in the range of 80–140 µm (Figure 2d). By adding glycerol as the plasticizer and also a high-*k* material in gelatin, the mechanical flexibility and effective dielectric constants were improved. The antenna (Figure 2e) is edible Au sputtered against a shadow mask on an edible printed circuit board (PCB) (Figure S2, Supporting Information) made of sugar paste. To compare with conventionally fabricated counterparts of these components utilized in electrical circuits, the ranges of the characteristics of these components were provided as the reference values. It is clear that the edible electrical components all exhibit comparable characteristics due to their counterparts in classical circuits. In addition to the food materials presented in Figure 2, more food materials have been utilized to build these components. Similar characteristics have been achieved as shown in the Supporting Information. It is thus convincing that edible food materials are able to build functional circuits.

Finally, several active constructs, i.e., systems with specific functionalities, including a pH sensor, a radio frequency filter, and a piezoelectric microphone, were fabricated and tested. The edible pH sensor consisting of Au–ZnO as working electrodes, an antenna made of Au for wirelessly transmitting signals, and an edible capacitor, was fabricated on a sugar paste substrate (**Figure 3**a,b). The reaction of ZnO with either acidic or basic solutions resulted in a change in the capacitance C between Au and ZnO electrodes, and thus the resonant frequency of the pH sensor changed with the pH value via $f = \frac{1}{2\pi\sqrt{LC}}$, where L is the inductance of the antenna that does not depend on the pH value. To validate and calibrate the edible pH sensor, the pH values of reference solutions were measured via a standard pH meter (Hanna Instruments); the capacitance of the Au–ZnO electrodes were characterized utilizing a probe station with precision LCR meter (Hewlett-Packard); and the resonant frequency of the pH sensor was detected by a circuit consisting of a reader, a differential amplifier, a signal generator, and an oscilloscope (Figure 3c). In the calibration, the edible pH sensors were immersed in the standard solutions with pH values from 1 to 12. As shown in Figure 3d, the capacitance varied with the pH values. Based on the measured pH-dependent capacitance C, the resonant frequency of the pH sensor was calculated using $f = \frac{1}{2\pi\sqrt{LC}}$, where L = 6.1 µH and was separately measured, which is also shown in Figure 3d. It is apparent that the calculated resonant frequency agreed very well with the measured values (Video S1, Supporting Information). Our results demonstrate that the edible pH sensor was able to measure the pH value of solutions that are both acidic and basic.

An edible radio frequency (RF) filter consisting of a resistor made of carbonized cotton candy and sweet potato starch, inductor made of carbonized cotton and sweet potato starch, and an edible capacitor was constructed and tested as to its frequency-dependent characteristics, as shown in Figure 3e. The values of the resistor, inductor, and capacitor were chosen for

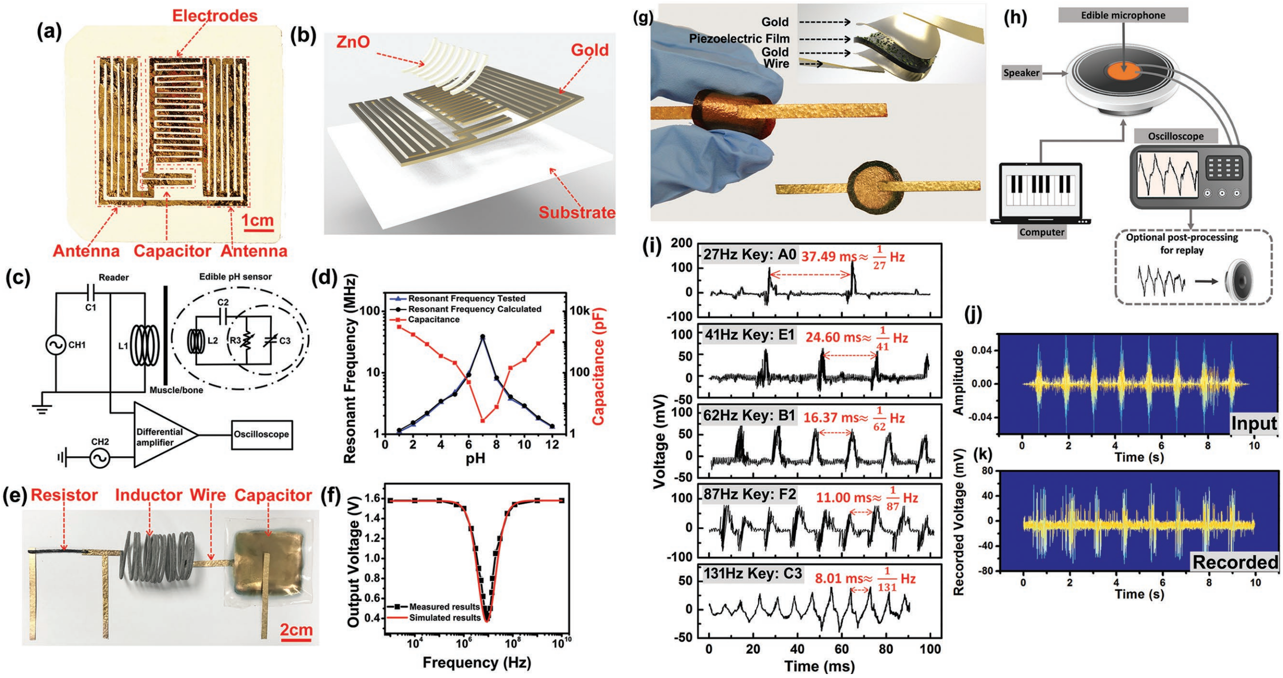

Figure 3. Results of edible functional electronic devices. a) Photograph of the edible pH sensor. b) Illustration of the edible pH sensor. c) Illustration of the working principal and detection scheme of the pH sensor. d) Characterization of the edible pH sensor in solutions with pH value from 1 to 12. e) A photograph of an edible RF filter. f) Frequency response of the RF filter. g) Photograph and illustration of the edible piezoelectric microphone. h) Illustration of the characterization procedure of the edible microphone. i) Recorded voltage waveform showing fidelity of the recorded sound using edible microphone. j) Amplitude of the input abdominal sound. k) Amplitude of the recorded abdominal sound.

the frequency range of interest, and were measured and verified individually ($R = 20\ \Omega$, $L = 0.2\ \mu\text{H}$, $C = 1.7\ \text{nF}$). This series RLC filter's frequency response was simulated, and measured with a signal generator and oscilloscope (Figure 3f), where good agreements between simulated and measured results were found and are shown. The edible RF filter clearly demonstrated a frequency response of a band reject behavior.

To demonstrate that the edible piezoelectric thin film can be used to convert mechanical vibration to appreciable voltage changes for potential biomedical applications, an edible piezoelectric microphone was built, in which a 2 mm thick edible piezoelectric thin film was coated with 200 nm thick Au electrodes on both sides (Figure 3g). To test the edible microphone, a sound with defined frequency generated from a computer (i.e., virtual piano keys) was played back via a loudspeaker where the edible microphone was firmly attached to the loudspeaker diaphragm to detect the mechanical vibration, with the edible microphone was connected to an oscilloscope to record and show the voltage waveform (Figure 3h). The recorded analog voltage signals from the oscilloscope were further fed to a loudspeaker for optional playback. Specific frequencies (ranging from 27 to 131 Hz) generated by the virtual piano keys (e.g., A0, C3) through a computer program matched very well with the recorded voltage waveform (Figure 3i), demonstrating that the edible microphone is able to record fidelity sound. It is noted that the waveform in Figure 3i represents averaged response so that the peaks are not evenly distributed. Video S2 (Supporting Information) shows a video of the recorded voltage waveform when a sound is played, followed by playback using the recorded voltage signals. Low-frequency sound is particularly important in biomedical applications as it is within the range of abdominal associated with both normal and pathologic conditions. To demonstrate the biomedical application, bowel sounds from a 70 year old man with abdominal pain[38] (Figure 3j) were fed to the loudspeaker and recorded via the edible microphone (Figure 3k). It was observed that the recorded voltage waveform successfully reproduced the original testing sound.

Food-based edible and nutritive electronics offer an advance in material considerations enabling the fabrication of devices and systems of potential use for the understanding of both normal physiology of the GI tract as well as abnormal states associated with a wide range of diseases (e.g., the gut microbiome and its influences on mental health). We envision a broad range of applications: from measurement of pH; GI motility; luminal bacterial content; and drug concentrations, to direct actuations, e.g., localized removal of cells and tissue for suspicious lesion (cancer) diagnostics, and therapeutics. Food-based materials also extend the spectrum of transient electronic materials for general nonmedical electronics applications, as new biodegradable and environmentally friendly materials for electronics. To further advance this field, new fabrication processes (e.g., 3D printing) will be useful to aid in the processing and formation of miniaturized devices. High-performance food-based semiconductor materials need to be identified and optimized, beyond the initial efforts (e.g., by Bauer and co-workers[39,40]). Continued definition of additional functional materials from food will further enrich this field for broader sensing and actuation capability.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

biodegradable materials, edible electronics, electronic devices, food materials, gastrointestinal tract

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[1] D. Fitzpatrick, *Implantable Electronic Medical Devices*, Elsevier, San Diego, CA, USA **2015**.
[2] E. Gibney, *Nature* **2015**, *528*, 26.
[3] J. A. Rogers, *JAMA, J. Am. Med. Assoc.* **2015**, *313*, 561.
[4] K. Kaewkannate, S. Kim, *BMC Public Health* **2016**, *16*, 433.
[5] A. Nathan, A. Ahnood, M. T. Cole, S. Lee, Y. Suzuki, P. Hiralal, F. Bonaccorso, T. Hasan, L. Garcia-Gancedo, A. Dyadyusha, S. Haque, P. Andrew, S. Hofmann, J. Moultrie, D. P. Chu, A. J. Flewitt, A. C. Ferrari, M. J. Kelly, J. Robertson, G. A. J. Amaratunga, W. I. Milne, *Proc. IEEE* **2012**, *100*, 1486.
[6] D. Y. Khang, H. Q. Jiang, Y. Huang, J. A. Rogers, *Science* **2006**, *311*, 208.
[7] D. H. Kim, J. H. Ahn, W. M. Choi, H. S. Kim, T. H. Kim, J. Z. Song, Y. G. Y. Huang, Z. J. Liu, C. Lu, J. A. Rogers, *Science* **2008**, *320*, 507.
[8] J. A. Rogers, T. Someya, Y. G. Huang, *Science* **2010**, *327*, 1603.
[9] D. J. Lipomi, M. Vosgueritchian, B. C. K. Tee, S. L. Hellstrom, J. A. Lee, C. H. Fox, Z. N. Bao, *Nat. Nanotechnol.* **2011**, *6*, 788.
[10] M. Ramuz, B. C. K. Tee, J. B. H. Tok, Z. N. Bao, *Adv. Mater.* **2012**, *24*, 3223.
[11] M. Vosgueritchian, D. J. Lipomi, Z. A. Bao, *Adv. Funct. Mater.* **2012**, *22*, 421.
[12] M. L. Hammock, A. Chortos, B. C. K. Tee, J. B. H. Tok, Z. A. Bao, *Adv. Mater.* **2013**, *25*, 5997.
[13] S. Xu, Y. H. Zhang, L. Jia, K. E. Mathewson, K. I. Jang, J. Kim, H. R. Fu, X. Huang, P. Chava, R. H. Wang, S. Bhole, L. Z. Wang, Y. J. Na, Y. Guan, M. Flavin, Z. S. Han, Y. G. Huang, J. A. Rogers, *Science* **2014**, *344*, 70.
[14] S. W. Hwang, H. Tao, D. H. Kim, H. Y. Cheng, J. K. Song, E. Rill, M. A. Brenckle, B. Panilaitis, S. M. Won, Y. S. Kim, Y. M. Song, K. J. Yu, A. Ameen, R. Li, Y. W. Su, M. M. Yang, D. L. Kaplan, M. R. Zakin, M. J. Slepian, Y. G. Huang, F. G. Omenetto, J. A. Rogers, *Science* **2012**, *337*, 1640.
[15] S. K. Kang, S. W. Hwang, S. Yu, J. H. Seo, E. A. Corbin, J. Shin, D. S. Wie, R. Bashir, Z. Ma, J. A. Rogers, *Adv. Funct. Mater.* **2015**, *25*, 1789.

[16] R. Wang, G. Blackburn, M. Desai, D. Phelan, L. Gillinov, P. Houghtaling, M. Gillinov, *JAMA Cardiol.* **2017**, *2*, 104.

[17] Y. Khan, A. E. Ostfeld, C. M. Lochner, A. Pierre, A. C. Arias, *Adv. Mater.* **2016**, *28*, 4373.

[18] A. Koh, D. Kang, Y. Xue, S. Lee, R. M. Pielak, J. Kim, T. Hwang, S. Min, A. Banks, P. Bastien, M. C. Manco, L. Wang, K. R. Ammann, K. I. Jang, P. Won, S. Han, R. Ghaffari, U. Paik, M. J. Slepian, G. Balooch, Y. G. Huang, J. A. Rogers, *Sci. Transl. Med.* **2016**, *8*, 366ra 165.

[19] L. Johnson, *Physiology of the Gastrointestinal Tract*, Academic Press, Cambridge, MA, USA **2012**.

[20] S. N. Adler, Y. C. Metzger, *Ther. Adv. Gastroenterol.* **2011**, *4*, 265.

[21] A. Kiourti, K. A. Psathas, K. S. Nikita, *Bioelectromagnetics* **2014**, *35*, 1.

[22] X. Wang, W. Xu, P. Chatterjee, C. Lv, J. Popovich, Z. Song, L. Dai, M. Y. S. Kalani, S. E. Haydel, H. Jiang, *Adv. Mater. Technol.* **2016**, *1*, 1600059.

[23] C. J. Ferris, *Soft Matter* **2009**, *5*, 3430.

[24] N. Gontard, S. Marchesseau, J. L. CUQ, S. Guilbert, *Int. J. Food Sci. Technol.* **1995**, *30*, 49.

[25] S. T. Parker, P. Domachuk, J. Amsden, J. Bressner, J. A. Lewis, D. L. Kaplan, F. G. Omenetto, *Adv. Mater.* **2009**, *21*, 2411.

[26] Y. J. Kim, W. Wu, S. E. Chun, J. F. Whitacre, C. J. Bettinger, *Adv. Mater.* **2014**, *26*, 6572.

[27] J. A. Cracknell, K. A. Vincent, F. A. Armstrong, *Chem. Rev.* **2008**, *108*, 2439.

[28] R. A. Higgins, *Materials for Engineers and Technicians*, Routledge, Abingdon, UK **2010**.

[29] C. Alexander, M. Sadiku, *Fundamentals of Electric Circuits*, 5th ed., McGraw-Hill Higher Education, New York City, NY, USA **2012**.

[30] E. Fukada, I. Yasuda, *J. Phys. Soc. Jpn.* **1957**, *12*, 1158.

[31] C. Halperin, S. Mutchnik, A. Agronin, M. Molotskii, P. Urenski, M. Salai, G. Rosenman, *Nano Lett.* **2004**, *4*, 1253.

[32] A. A. Marino, R. O. Becker, *Nature* **1975**, *253*, 42.

[33] J. Kim, S. Yun, Z. Ounaies, *Macromolecules* **2006**, *39*, 4202.

[34] J. Y. Fu, P. Y. Liu, J. Cheng, A. S. Bhalla, R. Guo, *Appl. Phys. Lett.* **2007**, *90*, 212907.

[35] R. Agrawal, H. D. Espinosa, *Nano Lett.* **2011**, *11*, 786.

[36] T. Kahlon, M. Chapman, G. Smith, *Food Chem.* **2007**, *100*, 1531.

[37] A. Gennadios, A. Handa, G. W. Froning, C. L. Weller, M. A. Hanna, *J. Agric. Food Chem.* **1998**, *46*, 1297.

[38] S. M. Al-Hilli, M. Willander, A. Öst, P. Strålfors, *J. Appl. Phys.* **2007**, *102*, 084304.

[39] M. Irimia-Vladu, E. D. Glowacki, P. A. Troshin, G. Schwabegger, L. Leonat, D. K. Suarova, O. Krystal, M. Ullah, Y. Kanbur, M. A. Bodea, V. F. Razumov, H. Sitter, S. Bauer, *Adv. Mater.* **2011**, *24*, 375.

[40] M. Irimia-Vladu, P. A. Troshin, M. Reisinger, L. Shmygleva, Y. Kanbur, G. Schwabegger, M. Bodea, R. Schwodiauer, A. Mumyatov, J. W. Fergus, V. F. Razumov, H. Sitter, N. S. Sariciftci, S. Bauer, *Adv. Funct. Mater.* **2010**, *20*, 4069.