Edible Electronics for Sustainable Agrifood: Towards the Integration of Edible Rechargeable Batteries with Sensor Networks

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Abstract — **As sensor networks become increasingly used in every step of the agricultural food chain, sustainability remains an underdeveloped aspect when implementing agrifood monitoring systems. Although electronics experienced exponential growth yielding to ultra-low power systems, most sensing nodes employ commercial batteries that are constituted by potentially harmful chemicals and might leak into the environment producing irreversible damage.**

Here we present a feasibility study aimed at demonstrating the compatibility of a recently developed edible rechargeable battery with commercial sensors for agrifood. The edible battery is completely made of edible materials, namely food-grade gold, ethyl cellulose, beeswax, activated carbon, riboflavin, quercetin, sodium hydrogen sulfate, and nori algae. As such, the battery does not contain any hazardous substances and can be disposed of by a variety of means, including composting. We demonstrate the integration of the battery with commercial thermistors and photoresistors to measure temperature and light intensity, respectively, which are relevant parameters in agricultural food production. We show that the performance of the edible battery is suitable for supplying power to commercial sensors therefore demonstrating its great potential for sustainable agrifood systems.

Keywords — ***Edible battery, edible electronics, biodegradable electronics, green electronics, agrifood sensors.***

I. INTRODUCTION

In the last decades the entire production chain of agricultural food, generally referred to as agrifood, has experienced a digital revolution that has transformed all the production stages including primary production, harvesting, storage, handling, transportation, processing, distribution, marketing, disposal, and consumption. The extensive use of sensors and their interconnected organisation into wired or wireless networks represent one of the major aspects of the digital revolution [1, 2]. A sensor network is a system composed of many sensing nodes spatially dispersed in a physical environment to monitor and collect real-time data relevant to the food production stage. In the particular case of primary production of agricultural food, sensor networks have been adopted to monitor several parameters, including temperature, light, humidity, pH, nutrients, and pollutants [2 - 4] yielding to commercially available products [5, 6]. The deployment of technology in the agricultural food primary production is used to support a management strategy that combines data and information from the field to take decisions and actions aimed at optimizing time, resources, and costs [2, 7, 8]. For instance, the temperature, of both air and soil, can be easily evaluated using thermocouples, resistance temperature detectors (RTDs), thermistors, and semiconductor-based temperature sensors [2]. Photosensors, such as photodiodes, photoresistors and phototransistors, have been largely used to monitor light exposure [3, 4]. Soil humidity can be monitored through interdigitated capacitive sensors, time-domain reflectometry or tailored impedance measuring systems, analysing how the moisture content in the soil affects its dielectric permittivity [2, 9]. pH can be monitored by exploiting different technologies: optical, electrochemical, or acoustic. There are also examples of conductometric sensors (conductive electrodes covered by a thin layer of pH-responsive material), ion selective field effect transistors (ISFET), or microcantilever-based pH sensors [2].

So far, the advancements in sensor networks mainly focused on improved interconnectivity (internet of things and communication strategies), performance enhancement (also using artificial intelligence), and power consumption minimisation. With specific reference to power consumption, extensive efforts have been made to reduce the power requirements of sensing nodes to the range of nW - µW, by optimising both the electronics and the communication strategies [10, 11]. However, the sustainability of the sensor network still remains an underdeveloped aspect. Sensing nodes are typically powered by batteries or solar panels. The exploitation of batteries can be an advantage in terms of space, costs, maintenance, and independence from solar exposure [12]. Sensing nodes are often dispersed widely throughout broad production facilities where they are exposed to atmospheric agents and therefore subjected to deterioration. The degradation of traditional batteries can release hazardous chemicals in the field. This represents a major hazard for the environment, wildlife, and, ultimately, for food consumers [13]. The geographical spread of the sensing nodes within a network also creates limitations in the continuous monitoring of the integrity of each sensing node, its recollection, and its disposal. Furthermore, various materials with different disposal needs are used to make sensing systems, creating a convoluted recycling process. As such, novel strategies are required to improve the sustainability of sensor networks.

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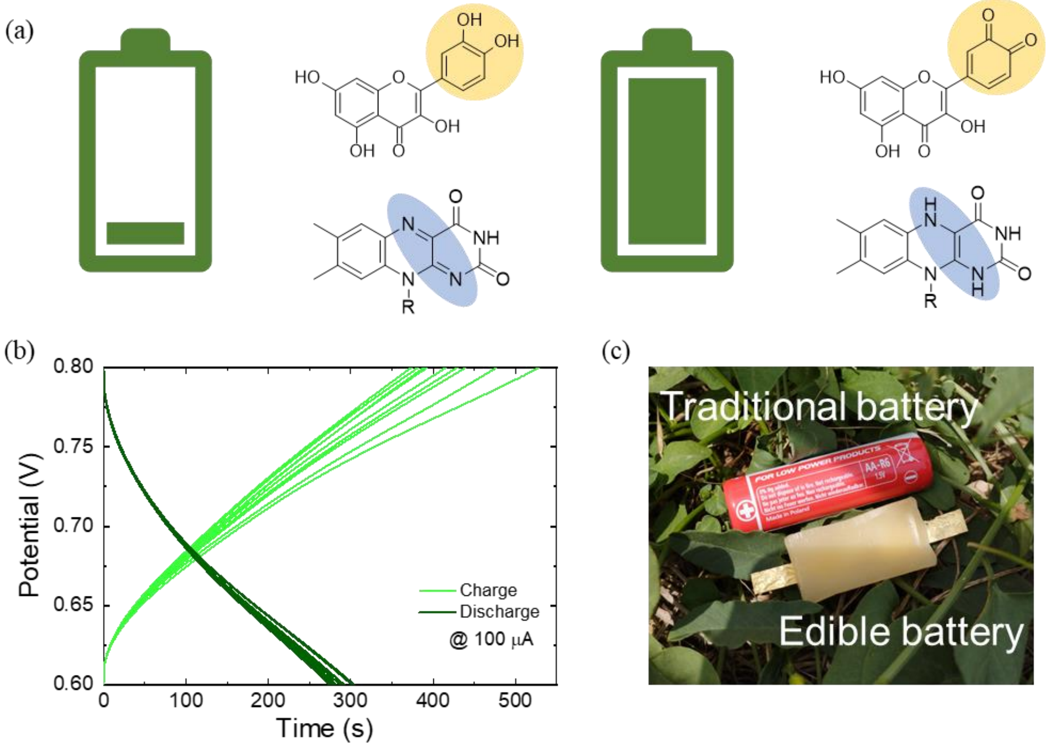

Fig. 1. (a) Edible redox-active molecules in the discharged and charged state. (b) Galvanostatic charging-discharging curves at 100 µA (cycles 2-10). (c) An edible battery vs. a traditional AA battery scattered in the environment simulating the application scenario.

Edible electronics can offer a potential solution. This emerging research field exploits food-derived materials and additives to develop electronic components, which can be potentially applied to the entire production chain of agricultural food [14]. Besides being fully biodegradable, edible electronic components have the advantage to be a cost-effective and safe-to-ingest technology, giving the possibility to integrate these devices directly on plants and fruits, without any need of recollection and disposal [14-16]. Also, electronic devices constituted by food-derived materials can be directly applied to food or included within the food packaging as there is no contamination risk. Recently, different edible or partly edible electronic components have been developed, ranging from electrodes [17, 18], transistors [19, 20] and sensors [21- 32], to communication systems [33], power sources [34-39], and robots [32]. As such, the possibility to integrate sensing nodes using edible components can represent an important step towards a more sustainable agrifood.

In this work, we present preliminary results aimed at demonstrating the use of edible energy sources in sensor networks for agrifood. For the first time, we present an integration between an edible power source and commercial sensors demonstrating their compatibility. In particular, we integrate our previously developed rechargeable battery to commercial temperature and light sensors, and we demonstrate comparable results to using a traditional power supply. We show that data has a high degree of similarity for both sensing applications with an average cross-correlation coefficient higher than 0.99. These findings indicate that edible alternatives can be adopted in lieu of traditional batteries, especially in the case of disposable and low-power applications.

II. THE EDIBLE BATTERY

The possibility to exploit edible electronic devices is strictly related to the development of edible power sources. Edible supercapacitors, which exploit the formation of an electrical double layer to store energy, have already been developed in recent years [34-37]. An edible fuel cell, which burns ethanol as fuel, has also been demonstrated although it exhibits a limited energy density [38]. In this frame, we recently developed an edible rechargeable battery, made entirely from food-grade materials [39]. We exploited two redox-active molecules, riboflavin and quercetin, as the anodic and cathodic materials, respectively (Fig. 1a). Riboflavin, commonly known as vitamin B2, is found in many different foods like almonds, egg white, and meat, and is sold also in the form of vitamin supplements and food colouring agents (E 101). Quercetin is a flavonol found in different vegetables and leaves, like capers, coriander, and kale. Activated carbon (AC), a food additive (E 153), was used to prepare composites with the small molecules to create a conductive path for electrons flowing to and from the redox centres. Active-redox inks were prepared by mixing the AC-small molecules composites with ethyl cellulose, used as a binder, dissolved in ethanol. The inks were then drop casted on conductive edible electrodes, made laminating edible gold leaves (E 175) onto ethyl cellulose (E 462) films. The battery was assembled by placing the anode and the cathode in a stacked configuration, using nori algae, previously soaked in the electrolyte (1 M water solution of $NaHSO_4$ (E 514ii)), as a separator. Finally, everything was encapsulated in beeswax (E 901). Besides being fully edible and biodegradable, the developed edible battery is also rechargeable, prolonging its lifetime and reducing waste. The full characterisation of the device is reported in [39].

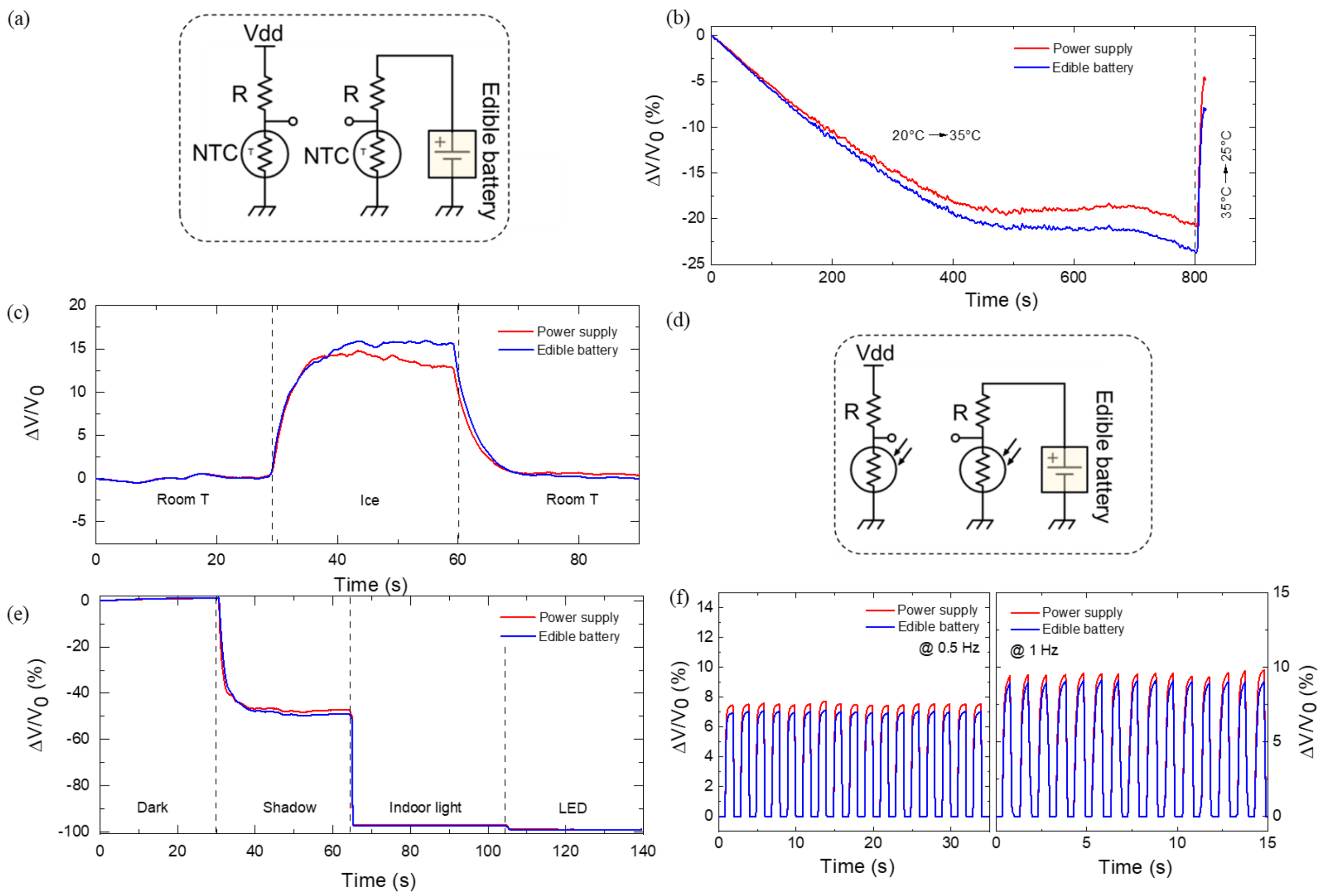

Fig. 2. (a) Schematic of the circuits tested for temperature sensing. The two test circuits are identical apart from the power source which is respectively a power supply and an edible battery. (b) Normalised output voltage variation from the two outputs during heating and cooling in an environmental chamber. (c) Normalised output voltage variation from the two outputs during cooling and heating using ice. (d) Schematic of the circuits tested for light intensity testing. (e) Normalised output voltage variation from the two outputs when exposing the circuits to different light conditions, i.e. dark, shadow, indoor light and direct light from a commercial LED. (e) Normalised output voltage variation from the two outputs when exposing the circuits to blinking light from a commercial LED at 0.5 Hz and 1 Hz.

III. RESULTS AND DISCUSSION

The edible batteries were fabricated as in [39] and tested before their use. We performed ten galvanostatic charging-discharging measurements at 100 µA between 0.6 and 0.8 V, using a MultiPalmSens4 potentiostat. The curves show a discharging plateau around 0.65 V and confirm the rechargeability of the batteries (Fig. 1b). The present implementation of the battery can deliver 100 µA for five minutes, corresponding to a capacity of ~9 µAh. The current implementation has an active area of 1 cm^2 and dimensions comparable to those of a traditional AA battery (Fig. 1c).

As a case study, we focused on temperature and light intensity sensing. To test the edible battery with a temperature sensor, a voltage divider circuit was first implemented using a discrete pull-up resistor (47 kΩ) and a commercial negative temperature coefficient thermistor (MF52B 100 kΩ at 25 °C). The voltage divider was connected to an edible battery using standard wiring. An identical voltage divider was also implemented, and 0.65 V was supplied with a power supply (Agilent E3647A). Both the circuits were exposed to identical controlled temperature changes and the output of both the voltage dividers were measured using a 2-channel precision source meter (Keysight B2912A). Fig. 2a shows a schematic of the two circuits under test.

In the first experiment, both circuits were introduced into an environmental chamber (Memmert HPP110ecoplus). It is worth mentioning that while the edible battery was also introduced into the environmental chamber, the power supply and the source meter were not introduced in the chamber and were connected externally through lateral cable windows. The chamber temperature was then gradually increased from 20 °C to 35 °C. Once the chamber temperature reached 35 °C, the chamber was opened to produce a cool-down effect. As shown in Fig. 2b, data from the temperature sensor powered by the edible battery and the power supply has a high degree of similarity, with a small deviation that might include the effect of the exposure of the battery to a different operating condition with respect to the power supply. In the second experiment, both circuits were exposed to a cooling source (ice bath) from room temperature condition. As shown in Fig. 2c, an expected resistance increase was observed producing a respective increase in the output of the voltage dividers. Also in this case, the output of the two circuits was highly compatible. To test the edible battery with a light intensity sensor, a similar voltage divider circuit was implemented using a pull-up resistor (47 kΩ) and a commercial photoresistor (GL5516) whose resistance is inversely dependent on the intensity of incident light. While this circuit was powered by the edible battery, an identical voltage divider was also implemented and powered up with 0.65 V from the same power supply (see Fig. 2d). Both circuits were first exposed to dark conditions. The light intensity was then progressively increased. Finally, the two circuits were directly illuminated using a white commercial LED. As expected, increased light intensity conditions created a reduction of the sensor resistance, which, in turn, produced a reduction of the output of the voltage divider. Data in Fig. 2e indicates a high similarity between the two signals. In a second experiment, the same testing circuits were exposed to intermittent light from a commercial white LED with frequencies of 0.5 Hz and 1 Hz (see Fig. 2f). Output data exhibited high compatibility also in this case.

To quantify the similarity between the two test conditions, we calculated the cross-correlation coefficient in each of the test using a Matlab custom algorithm. For the temperature and light intensity sensing, we observed average cross-correlation coefficients of 0.9961 and 0.9995, respectively. The slight deviations are probably to be attributed to device-to-device variations and measurement errors.

Although we provide a preliminary proof-of-concept, the possible implementation of edible batteries in low-power sensor networks for agrifood in a real-life scenario will require performance optimization and a systematic evaluation of the environmental impact of these devices. Different tests will be carried out to study the degradation mechanism and the lifetime of the battery in different environmental conditions. For the present implementation of the battery, we estimate the lifetime of the battery to be in the range of three hours when supplying the circuit with a continuous current of 1 µA. This figure can be increased by operating the system at low sampling frequency and by implementing energy-saving design strategies. Research efforts aiming at improving the performance of the battery are also ongoing, with particular focus on its capacity and dimensions. Furthermore, the digestibility of all the battery components will be also evaluated to avoid any possible threats after ingestion for wildlife and humans.

IV. CONCLUSIONS

The integration of edible electronic components in sensor networks for agrifood monitoring can have a significant impact in terms of sustainability and food safety. Edible power sources are particularly attractive to reduce the risks related to food contaminations, environmental pollution, and threats to wildlife. Here we demonstrate the integration of an edible rechargeable battery with commercial sensors, showing the potential application in agrifood low-power sensor networks. In particular, we used the edible battery to power commercial temperature and light sensors, acquiring data comparable to those obtained by powering the sensors with a traditional power supply. In our feasibility study, we observed an average cross-correlation coefficient higher than 0.99 between data collected from sensing circuits powered with the edible rechargeable battery and a benchtop power supply. These findings suggest that adopting an edible battery is not detrimental to the quality of data and therefore can be considered as a potential alternative to traditional batteries to improve the sustainability of sensors networks applied to agrifood.

Next steps include the improvement and development of our edible rechargeable battery to increase its performance in terms of capacity and shelf life, evaluating in parallel its environmental impact and economic feasibility. We are also testing the integration of edible batteries with other different edible electronic components like sensors and simple logic circuits, with the aim to develop fully edible sensor systems with potential applications in both medical diagnostics and food monitoring.

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