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Unconventional Electronic Devices

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Abstract – *Alternative materials for electronic components are being investigated to address environmental concerns associated with electronic waste and enable new approaches to temporary biomedical sensing. In this article, we present research on green and edible electronics conducted at the Faculty of Technical Sciences, University of Novi Sad. Substrates prepared from fruit and vegetable residues and cookie-dough ingredients have been used for the fabrication of functional components and circuits, including capacitors, voltage dividers, and resonant structures. Temperature sensing has been demonstrated using apple-pomace-based components, through which the oral temperature of a healthy volunteer was measured. Commercially available and reused chewing gum have also been investigated for basic electronic components and mechanical-force sensing, while an edible bite-force sensor has been developed for oral applications. Furthermore, inductors have been constructed from spaghetti coated with edible gold leaf, and a fully edible passive resonant circuit has been demonstrated at approximately 200 MHz. Through these examples, possibilities for electronic functionality based on food-derived materials are illustrated. Particular attention focuses on temporary oral sensing and the use of renewable resources and food-processing by-products. Material variability, moisture sensitivity, and operational stability must be addressed, while safety, biological compatibility, and biodegradability must be assessed for complete devices before broader practical application.*

Keywords: unconventional electronics, green electronics, waste electronics, textile electronics, sensors, biomedical

1. INTRODUCTION

Is it possible to use a banana peel in an electronic circuit? Could potato peels help track our heartbeat? Might our clothes and socks one day monitor our health?

These questions might seem odd at first, but in the lab for unconventional electronics, at the Faculty of Technical Sciences, University of Novi Sad, the team and I have been working on them and finding solutions for several years.

Modern society depends on electronics. Electronic technologies are now an integral part of everyday life. This includes mobile phones and computers, as well as medical equipment and devices that track our health 24/7. However, their increasing use also creates an important environmental challenge: electronic waste. Most conventional electronic devices contain materials that are difficult to recycle or remain in the environment long after their intended use. This raises an important question: do all electronic components really need to be manufactured from conventional industrial materials?

The team for unconventional electronics is looking at alternative approaches in green, edible, and textile electronics. The concept is fairly simple. To look into whether materials found in nature, food waste, and even everyday fabrics can be used as a substitute for traditional materials to be converted into working electronic components and devices. An introductory view of these substitutions and the head of the lab can be seen in Figure 1.

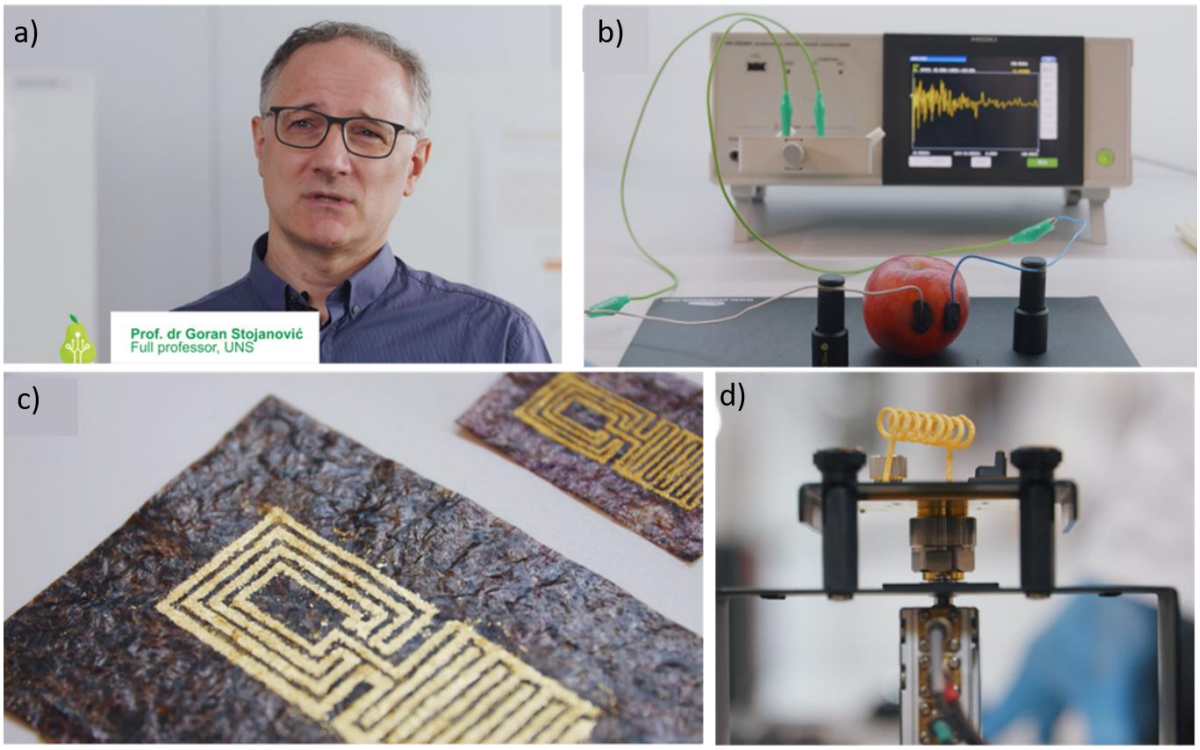


Figure 1. The goal of unconventional electronics is to repurpose food waste: a) Prof. Dr Goran M. Stojanović; b) Impedance measurement with edible electrodes; c) Seaweed resonant circuits; d) Edible gold inductors during measurement.

2. GIVING FOOD WASTE A SECOND LIFE

One of the most interesting directions of the team's research involves transforming food waste into useful electronic materials. If a banana peel, orange, lemon, or potato is viewed or considered, it is most likely to be discarded after the edible part has been consumed. In this laboratory, however, they are viewed differently.

Methods have been developed to process fruit and vegetable peels into powders and subsequently prepare substrates suitable for electronic components. These substrates provide the physical support on which electrical structures can be manufactured. Conducted experiments have demonstrated that their mechanical and surface properties can be comparable to those of certain commercially available materials.

With these surfaces made from recycled food waste, the team has built working capacitors and resonant circuits [1,2].

What matters most about these results is not just turning waste into something useful but showing that these unusual materials can really work in electronics. Rather than seeing agricultural leftovers as just waste, they can be seen as resources for future sustainable technology.

3. ELECTRONIC SENSORS THAT COULD WORK INSIDE THE MOUTH

In another important area of our work, electronic sensors are being developed for applications in the human oral cavity. As is often emphasized, our research is guided by the "3 P's"—People, Pets and Plants—and their well-being is intended to be supported through its outcomes.

The mouth provides valuable information about human health. Useful indications of physiological processes and oral conditions can be provided by changes in temperature, acidity and other properties of saliva. Commercial sensors are generally manufactured from materials that are not intended to be swallowed or that are not degraded inside the human body. Therefore, the possibility of fabricating sensors from materials intended to be swallowed and absorbed by living organisms has been investigated [3]. As one example, temperature-sensitive electronic components have been developed using natural and polymer-based materials, including those derived from apple pomace, a by-product of apple processing. Changes in the electrical resistance of these components were demonstrated as the temperature was varied. Temperature can therefore be determined from measurements of this variation. In particular, the oral temperature of a healthy volunteer was measured using an apple-pomace-based sensor. Through this demonstration, a significant step was taken towards electronic devices intended for temporary operation in the mouth, with materials selected based on their biodegradability and potential biological compatibility [4].

4. WHAT CAN CHEWING GUM TELL US?

Chewing gum has also been investigated as an everyday material for oral electronics. Its flexibility, ready availability and low cost, together with its intended use in the oral cavity, have been regarded as particularly favourable characteristics for the exploration of unconventional electronic structures. In our laboratory, both commercially available and reused chewing gum were investigated as materials for the construction of basic electronic components. Resistors, capacitors, inductors and antenna structures were demonstrated, together with a sensor through which mechanical force could be detected [5]. Particular biomedical relevance can be attributed to this application, since useful information for dental research and the investigation of chewing-related functions can be obtained from measurements of forces in the mouth. An edible bite-force sensor has also been developed by our team, through which another approach to mechanical-force measurement with materials intended for oral applications has been demonstrated. More broadly, inexpensive, flexible and potentially biodegradable materials are being investigated for the development of less intrusive and more sustainable sensors [6].

5. FROM COOKIE DOUGH TO ELECTRONIC CIRCUITS

A material more commonly associated with baking than with engineering has also been explored in our laboratory: cookie dough. A familiar material was sought through which mechanical support could also be provided. Following appropriate processing, its performance was found to be comparable to that of commercially available rigid electronic substrates. In this research, an edible substrate was developed from cookie-dough ingredients, and its mechanical and electrical properties were investigated. Functional electronic circuits, including a voltage divider and a resonant circuit, were subsequently demonstrated on the substrate [7]. The devices were examined under different conditions, including environments intended to reproduce some of the challenges encountered inside the mouth. Their electrical behaviour was also investigated as temperature and acidity were varied. Although this technology is still being investigated at the research stage, new possibilities for disposable and environmentally conscious sensing systems have been identified.

6. SPAGHETTI AND GOLD: A RENAISSANCE COMBINATION

Some of the most visually surprising results of our research have been obtained through the development of electronic components from spaghetti. Through these results, it has been demonstrated that edible electronics need not be restricted to simple measurements. Food-based components can also be operated at radio frequencies, which are used in numerous sensing and communication systems. In collaboration with international research partners, functional inductors, also known as solenoids, were constructed from spaghetti coated with edible gold leaf. Inductors are used as essential components in many electrical circuits, in which interactions with magnetic fields are exploited. Through the combination of these food-based structures with other edible components, a fully edible passive resonant circuit was demonstrated at an operating frequency of approximately 200 MHz [8]. A considerably broader range of materials than previously assumed may therefore be considered for electronics engineering.

7. WHY DOES THIS MATTER FOR THE ENVIRONMENT AND HUMAN HEALTH?

Two important objectives are addressed through the development of green and edible electronics: a reduction in the environmental impact of technology and the introduction of new methods for biomedical monitoring. From an environmental perspective, alternatives to some traditional manufacturing methods are provided through the production of electronic components from renewable materials or residues from the food-processing industry. In healthcare, devices for temporary sensing could one day be constructed from carefully selected biocompatible and biodegradable materials, particularly where difficulties would be encountered in the removal of a conventional device. At the same time, edibility or environmental harmlessness should not be assumed solely on the basis of the inclusion of a food-based material. All components, including the substrate, conductive layers, electrical contacts and other elements, must be assessed. For a completely edible electronic device, compliance with the relevant safety standards must be ensured for every constituent material. Similarly, biodegradability must be evaluated for the entire device under the conditions in which it is discarded.

In our research, therefore, the demonstration of new electronic functions is accompanied by investigations of the materials, their stability, their physical properties and their behaviour under relevant operating conditions.

8. RESEARCH FROM NOVI SAD WITH AN INTERNATIONAL PERSPECTIVE

These developments have been achieved through the work of our team at the Faculty of Technical Sciences, University of Novi Sad, together with colleagues from other scientific institutions. Our research has been advanced through international cooperation, particularly within European projects focused on green electronics,

sustainable materials and biomedical technologies. Through projects such as GREENELIT and EINSTEIN, an important framework has been provided for the integration of expertise in electronics, materials science, food technology and biomedical engineering.

An interdisciplinary approach is therefore considered essential. For the development of edible electronics, traditional circuit design must be complemented by an understanding of the behaviour of natural materials, the changes induced by moisture and temperature, and the methods by which electronic structures can be fabricated while their intended functions are preserved.

Through our experiments involving food waste, chewing gum, cookie dough and spaghetti, it has been demonstrated how solutions can be generated through collaboration between different scientific disciplines, even where they might otherwise not have been readily envisaged.

9. THE FUTURE OF ELECTRONICS MAY BE CLOSER TO NATURE THAN WE THINK

Food-based electronics should not be expected to replace conventional computers, smartphones or advanced medical equipment in the near future. Their greatest potential may instead be found in applications in which electronic functionality is required only temporarily, particular importance is attached to environmental impact, or close interaction with the human body is required. Considerable challenges must still be addressed. Variations in the composition of natural materials, moisture absorption, changes in mechanical properties and differences between manufacturing batches must all be taken into account. Reliability, reproducibility and safety must be ensured, and these aspects are also being addressed in our ongoing work.

Nevertheless, our research has shown that we can manufacture electronic components from materials commonly encountered in everyday life. A discarded fruit peel can be used as an electronic substrate. A piece of chewing gum can be incorporated into a force sensor. Cookie dough can be used to support an electrical circuit. Spaghetti coated with edible gold can be operated as an electronic inductor. These examples should be regarded as more than scientific curiosities. Through them, a reconsideration of the relationship between technology, natural resources, and the environment is encouraged. This comes to reality in the laboratory for unconventional electronics, shown in Figure 2.



Figure 2. Laboratory for unconventional electronics

The future of electronics should be assessed not only by the size, speed or power of devices, but also by the responsibility with which they are manufactured, used and disposed of.

10. CONCLUSION

The research presented has demonstrated the feasibility of fabricating functional electronic components and sensors from food waste and everyday food-based materials. Fruit and vegetable residues have been processed into substrates suitable for electronic structures, while temperature and mechanical-force sensing have been demonstrated using selected materials intended for oral applications. Through circuits fabricated on cookie-dough substrates and resonant structures assembled with gold-coated spaghetti, the application of these materials has been extended from basic circuit functions to operation at radio frequencies. These findings provide a basis for further investigation of electronic devices intended for temporary use, particularly in oral monitoring and disposable sensing applications. For broader practical application, variations in material composition, moisture absorption, and changes in mechanical and electrical properties must be addressed through controlled processing and characterization under relevant operating conditions. Edibility, biological compatibility, and biodegradability must be evaluated for the complete device, including its substrate, conductive layers, contacts, and other constituent materials. Similarly, environmental benefits must be established under the intended conditions of manufacture, use and disposal. Further development should therefore be supported by interdisciplinary cooperation, through which material selection, fabrication, electronic performance and the intended application can be considered together. In this way, functional electronic technologies can be developed with greater attention to natural resources, temporary biomedical use and responsible disposal.

DECLARATIONS

The authors declare no conflict of interest. The data availability is not applicable.

REFERENCES

[1] Radovanović, M. R., Stojanović, G. M., Simić, M., Suvara, D., Milić, L., Kojić, S., and Škrbić, B. D. (2024). “Edible Electronic Components Made from Recycled Food Waste.” Advanced Electronic Materials, 10(7), 2300905. DOI: 10.1002/aelm.202300905

[2] Stojanović, G. M., Popović, Ž., Milić, L., and Simić, M. (2024). “Potato Peels-Based Electrodes for Recording ECG and EMG Signals.” Sensing and Bio-Sensing Research, 44, 100664. DOI: 10.1016/j.sbsr.2024.100664

[3] Vejin, M., Đoćoš, M., Pojić, M., Terek, P., Kojić, S., Bobić, Z., Petrović, B., and Stojanović, G. (2022). “Edible Sensor for Electric Impedance Spectroscopic Analysis of Bioactive Liquids Containing Silver Nanoparticles.” IEEE NAP 2022, conference paper.

[4] Stojanović, G. M., Radovanović, M., Kojić, S., Milić, L., Simić, M., Kojić, T., Duval, R. G., Vukmirović, J., and Petrović, B. (2024). “Temperature Sensors Manufactured from Edible Materials Intended for Oral Cavity Operation.” International Journal of Precision Engineering and Manufacturing-Green Technology, 11, 221–231.DOI: 10.1007/s40684-023-00535-2

[5] Stojanović, G., Novaković, B., and Petrović, B. (2023). “Design, Fabrication and Testing of Chewing Gum-Based Electronic Components and Sensors.” IEEE EUROCON 2023, 536–541. DOI: 10.1109/EUROCON56442.2023.10198997

[6] Milić, L., Kojić, S., Qureshi, S., Simić, M., Duval, R. G., Petrović, B., and Stojanović, G. M. (2024). “Edible Bite Force Sensor: A Novel Approach to Measuring Bite Force in Biomedical and Dental Applications.” Medical Science Monitor, 30, e944050. DOI: 10.12659/MSM.944050

[7] Milić, L., Popović, Ž., Mišić, I., Luzio, A., Caironi, M., and Stojanović, G. M. (2024). “Electrical Circuits Developed on Cookie Dough-Based Substrate and Their Sensing Applications.” IEEE Sensors Letters, 8(12), 2001404. DOI: 10.1109/LSENS.2024.3497924

[8] Radovanović, M. R., Popović, Ž., Kojić, S., Piper, D., Luzio, A., Bonacchini, G. E., Caironi, M., and Stojanović, G. M. (2025). “Fully Degradable Food-Based Solenoids and Radio Frequency Circuits for Green Electronics.” Advanced Engineering Materials, 27(4), 2401790. DOI: 10.1002/adem.202401790

AUTHOR BIOGRAPHIES



Goran M. Stojanović, https://www.stojanovicgoran.com, is a full professor at the Faculty of Technical Sciences (FTS), University of Novi Sad (UNS), Serbia. He received a BSc, MSc and a PhD degree in 1996, 2003 and 2005, respectively, from FTS-UNS, all in electrical engineering. He has 27 years of experience in R&D. His research interests include sensors, flexible electronics, textile electronics, edible electronics and microfluidics. He is an author/ co-author of 391 articles (h-index 38, with 5987 citations), 5 books, 3 patents, 1 chapter in monograph. He was keynote speaker at 12 international conferences as he was a supervisor of 13 PhD students, 40 MSc students and 60 diploma students at the FTS-UNS. He has more than 17 years' experience in coordination of EU funded projects (Horizon Europe, H2020, EUREKA, ERASMUS, CEI), with total budget exceeding 18.86 MEUR. Currently, he coordinates 5 Horizon projects, in the field of green electronics and textile electronics.



Sanja Kojić is an Assistant Professor at the Faculty of Technical Sciences (FTS), University of Novi Sad (UNS), Serbia. She received an MSc degree in 2010, and a PhD degree in 2022 from FTS-UNS, in electrical engineering. Author of over 100 articles, including over 80 in leading peer-reviewed journals with impact factors and one patent. Her scientific papers have been cited 825 times and her h-factor is 15. Her areas of research cover microfluidics, flexible, printed and green electronics, mechanical and microscopic characterization, and archaeology. Mrs. Kojić has more than ten years of work experience on national and international projects (Horizon Europe, H2020, FP7, ERASMUS, TEMPUS, COST). She runs a volunteering program at Engineering Creativity Center of the University of Novi Sad, where students can get access and training to the newest fabrication equipment for the textile, flexible and printed electronics as well as microfluidic chips.



Lazar Milić is a researcher at Department of Power, Electronics and Telecommunication, Faculty of Technical Sciences, University of Novi Sad. He is currently pursuing a doctorate in electronics, under the mentorship of Professor Goran M. Stojanović. Under his mentorship, he has done his bachelors thesis in the field of textile electronics, applied in biomedical engineering, as well as his master thesis in the field of edible electronics, again applied in biomedical engineering. Aside from the aforementioned fields, his interests lie in micro and nano electronics, as well as bioelectronics and biosensors. He has published 40 journal and conference papers in the past 6 years, gaining 209 citations and an h-index of 8 during that time. His ResearchGate is https://www.researchgate.net/profile/Lazar-Milic/research.