De Remediis
ISSN: 3058-0358
Official Scientific Journal of Faculty of Pharmacy UD

Review

From toxic materials to food-grade materials: A major challenge for battery design – A mini review

Marina Le Borgne[1,#], Perrine Ximenes[2,#] and Marc Le Borgne[2,3*]

1 Faculté de Médecine Lyon-Est, Université Claude Bernard Lyon 1, Univ Lyon, 69373 Lyon, France
2 Centre de recherche en cancérologie de Lyon, Centre Léon Bérard, CNRS 5286, INSERM 1052, Université Claude Bernard Lyon 1, Univ Lyon, 69373 Lyon, France
3 Musée Ampère, 300 route d'Ampère, 69250 Poleymieux au-Mont-d'Or, France
* Correspondence: marc.le-borgne@univ-lyon1.fr
# Contributed equally

Abstract

The use of batteries, found in telephones, remote controls, and medical devices, is an integral part of our daily lives. Unfortunately, the routine use of these electronic devices has harmful effects on the environment, primarily due to the pollution generated by heavy metals. This article traces the history of batteries, starting with the birth of the voltaic battery in 1799, invented by Alessandro Volta. This discovery, based on the principle of redox reactions between zinc and copper, was subsequently taken up and improved on numerous times. In 1836, John Frederic Daniell designed a two-compartment cell, stabilized by depolarizers and connected by a salt bridge. To meet today's climate challenges, researchers continue to design batteries, but this time they are biodegradable, edible, rechargeable, and therefore sustainable. In recent years, we have seen the emergence of highly innovative concepts. Some scientists, for example, are using cuttlefish ink to extract melanin. In a sodium-ion battery, this molecule acts as a natural anode, enabling sodium ions to be stored and thus contributing to the device's eco-friendliness. Other innovative research has also emerged, using other natural ingredients such as quercetin and riboflavin. These technological advances are of particular interest to the healthcare sector for the development of implantable medical devices.

Keywords: implantable medical devices, edible batteries, sustainable, rechargeable, natural ingredients.

1. Introduction

At work or at home, we all use mice, watches, electronic toys, and remote controls. But for these objects to work, they must contain an electric battery. This converts chemical energy into electrical energy through a redox reaction. Objects fitted with these batteries have one major weakness: the danger they pose to our ecosystem. In 2022, 244,000 tons of portable batteries were sold in the EU[1]. In the same year, 111,000 tons of used portable batteries were collected for recycling, but how many end up in our rubbish bins and in our environment? Since 2006, the European directive 2006/66/EC on portable batteries and accumulators[2] has also sought to improve the management of waste batteries and accumulators. The figures for 2022 show just how difficult it is to collect this type of polluting waste.

The healthcare sector is also a major consumer of batteries, to ensure the optimal functioning of a large number of medical devices such as wireless capsule endoscope[3,4], implantable orthodontic system[5], implantable cardioverter-defibrillator[6], fully implantable and rechargeable artificial pancreas[7], and vibrating ingestible bioelectronic stimulator[8] (Table 1).

Medical device	**Battery**	**Application**	**Year of publication (reference)**
capsule endoscope	2 silver oxide batteries	exploration of GI tract (detection, evaluation, surveillance)	2000 (3)
implantable orthodontic system	1 lithium-ion battery	integrated intra-oral phototherapeutic device (bone regeneration)	2017 (5)
implantable cardioverter-defibrillator	1 hybrid cathode lithium battery	defibrillation	2022 (6)
artificial pancreas	1 lithium-ion battery	intraperitoneally release of insulin	2023 (7)
vibrating stimulator	1 silver oxide battery	luminal vibratory stimulation	2023 (8)
implantable battery	1 zinc-oxygen battery	electrical stimulation	2023 (9)
vitals-monitoring pill	2 silver oxide batteries	breathing and heart rate monitoring (sleep apnoea and detection of opioid overdoses)	2023 (10)

implantable closed-loop detection device	1 lithium-ion battery	opioid safety	2024 (11)

***Table 1**: Some examples of battery-powered devices used in medical devices.*

It is therefore appropriate to first examine the basic principle of the battery, then present new approaches using natural compounds, enabling the design of eco-friendly, even edible batteries.

2. Birth of the voltaic cell and its improvement by John Frederic Daniell

In 1799, the Italian physicist Alessandro Volta (1745-1827) created the first battery to emit direct current, known as the voltaic battery. To do this, he successively stacked pairs of zinc-copper discs (20 to 60 pieces per metal) separated by pieces of cloth soaked in a dilute sulphuric acid solution (or brine - an aqueous solution of a salt such as Na^+Cl^-), which acted as the electrolyte (Figure 1). He also added a metal wire to connect the two ends of this stack, which were zinc (negative pole) and copper (positive pole). With the circuit connected and closed, an electric current was able to flow[12]. At the anode (negative pole), he observed an oxidation reaction in which Zn(s) gave Zn^{2+} according to equation 1:

$$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^- \ (eq. 1)$$

and at the cathode (positive pole), he observed a reduction reaction in which Cu^{2+}(aq) gave Cu(s) according to equation 2:

$$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s) \ (eq. 2)$$

Unfortunately, the water present can also react according to the following equation:

$$2\,H_2O + 2e^- \rightarrow H_2 + 2\,OH^- \ (eq. 3)$$

The release of H_2 limits the reduction reaction. The released H_2 can also oxidise to H_2O, a process known as electrode polarisation.

Stacking the layers [zinc + electrolyte + copper] in series produces a higher electrical voltage (measured in volts, denoted V), proportional to the number of layers, and therefore releases more electrical energy. For example, a stack of around twenty layers generates a voltage of around 20 V on a voltmeter, and an electric current of around twenty mA on an amperemeter (mA for milliampere, one of the seven base units of the international system of units)[13].

A number of limitations became apparent, such as its lack of watertightness and the fairly rapid corrosion of the discs. Nevertheless, the main limitation of this device was the reaction between the water and the electrons produced by the oxidation of Zn(s). In the end, the Volta battery did not provide a very stable voltage with this polarisation of the electrodes. Nevertheless, in 1813, Napoleon I ordered the manufacture of a Volta battery with around 600 discs. The success of Volta's invention was international and led to a cascade of discoveries, such as the connection between electricity and magnetism by Hans Christian Ørsted (1820)[14], the interpretation of the phenomenon of magnetism by the theory of André-Marie Ampère's molecular currents (1821)[15], and Michael Faraday's discovery of induction (1831)[16].

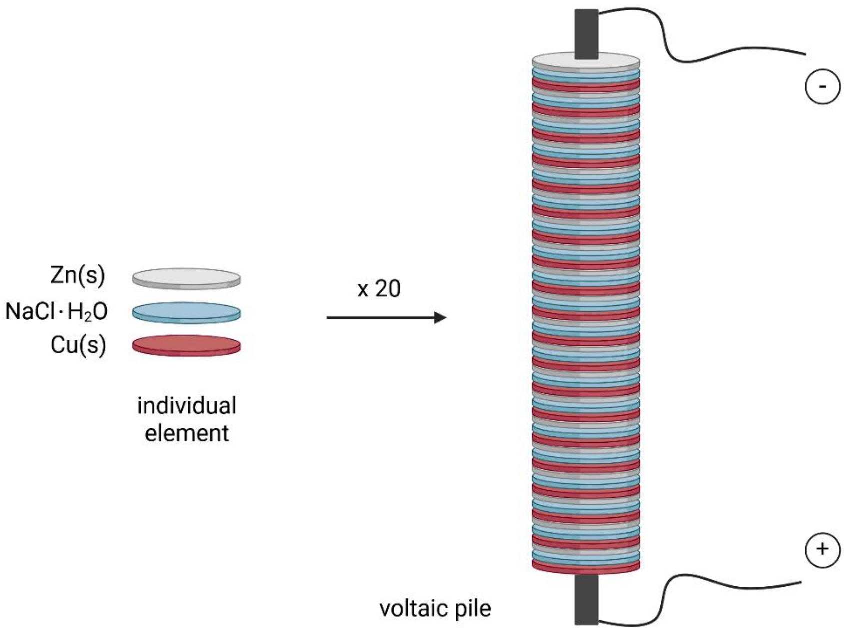

***Figure 1**:* Principle of a voltaic column (Created with BioRender.com).

Other scientists then set about perfecting this first device. In 1836, the British chemist and meteorologist J.F. Daniell (1790-1845) created a battery based on a slightly different mechanism, inspired by the operating principle demonstrated by Antoine-César Becquerel (1788-1878). He used depolarisers such as manganese dioxide MnO_2 to block polarisation of the electrodes[17]. In summary, the Daniell cell[18] (Figure 2) consists of 2 separate compartments, called half-cells, each containing an oxidant-reductor pair:

- The $Zn/ZnSO_4$ pair, which will be the negative pole, is known as the anode,
- The $Cu/CuSO_4$ pair, which will be the positive pole, is known as the cathode.

The two poles are then connected by a metal wire to ensure the flow of electrons. An electrolyte bridge (for example a salt bridge containing potassium nitrate, KNO_3) is added to close the circuit and thus ensure the electrical neutrality of the solutions in the two half-cells. This electrolyte bridge can also be a porous wall permeable to ions. Two chemical reactions are observed, one at the anode (oxidation reaction) with Zn(s) according to equation 1 and one at the cathode (reduction reaction) with Cu^{2+}(aq) according to equation 2. The overall equation for this redox reaction is given by equation 4 as follows:

$$Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)\ (eq.4).$$

The displacement of electrons creates an electric current, the intensity of which is measured by an amperemeter. The circulation of nitrate ions (NO_3^-) and potassium ions (K^+) will ensure the electrical neutrality of the system. We can also refer to the reaction quotient (Q_r), which is used to assess the battery wear and tear. Last but not least, the Daniell cell is not rechargeable because of the limited reversibility of the reactions, but the voltage is very stable. Among other things, this system enabled the development of the telegraph.

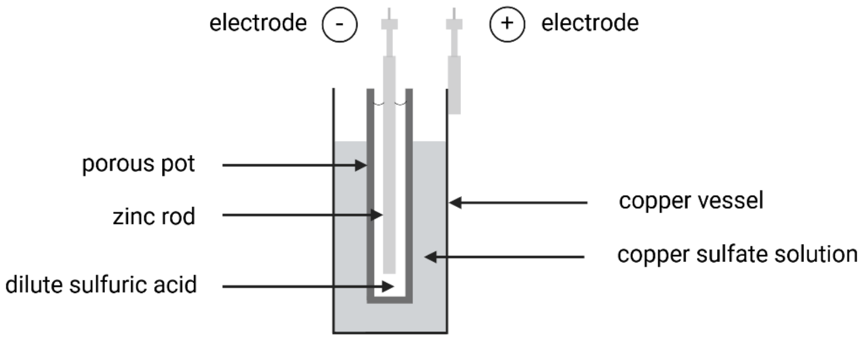

Figure 2: Principle of a Daniell cell (Created with BioRender.com).

Between 1799 and 2025, cells and batteries were gradually modernised, becoming more powerful, longer-lasting, and more miniaturized, but always respecting Volta's initial principle (a cathode, an anode and electrolytes), greatly improved by J.F. Daniell and other inventors. For example, in 1859, Gaston Planté (1834-1889) designed the first lead/acid accumulator, considered to be the first rechargeable electric battery[19]. As a result, the range of metals used has also broadened, including cadmium, lead, zinc, manganese, nickel, silver, mercury, and lithium[20]. Then who has not thrown a battery into nature? Heavy metal pollution has become a scourge for our ecosystem! Who has not dreamed of designing an eco-friendly battery?

3. Design a sodium-ion cell from *Sepia officinalis* ink

A study published in the *Proceedings of the National Academy of Sciences of the United States of America* (Proc. Natl. Acad. Sci. U.S.A.) in 2013 demonstrated the benefits of using melanin and manganese oxide electrodes to design a sodium-ion battery[21]. Melanin is a pigment found in our eyes, hair, and skin, but also in our brains (Figure 3). In this study, they are going to extract it from cuttlefish ink (*Sepia officinalis*) and use it as a natural anode. With just 300 mg of eumelanin (one of the constituents of melanin), it is possible to manufacture an anode of the eumelanin type charged with Na^+ ions, combined with a manganese oxide (MnO_2) cathode. The result is an eco-compatible battery made from compounds naturally present in the human body. This battery has the following characteristics: initial potential of 1 V with a maximum specific capacity of 16 mA h g^{-1}.

A more recent study presented in 2016 at the 252nd ACS meeting[22] also uses melanin as an electrode in an aqueous sodium battery. The researchers are working on a pill that could monitor gastric problems. In the event of the battery getting stuck in the digestive tract, the materials we use are digestible and could disintegrate in a few weeks. A big advantage over synthetic materials that would have to be surgically extracted.

Thanks to its particular structure (tyrosine polymer), melanin is a fairly magical biomaterial, capable of interacting with ions and metals, the basic elements of batteries. Its properties make it a macromolecule that can act as both an anode and a cathode, depending on the application.

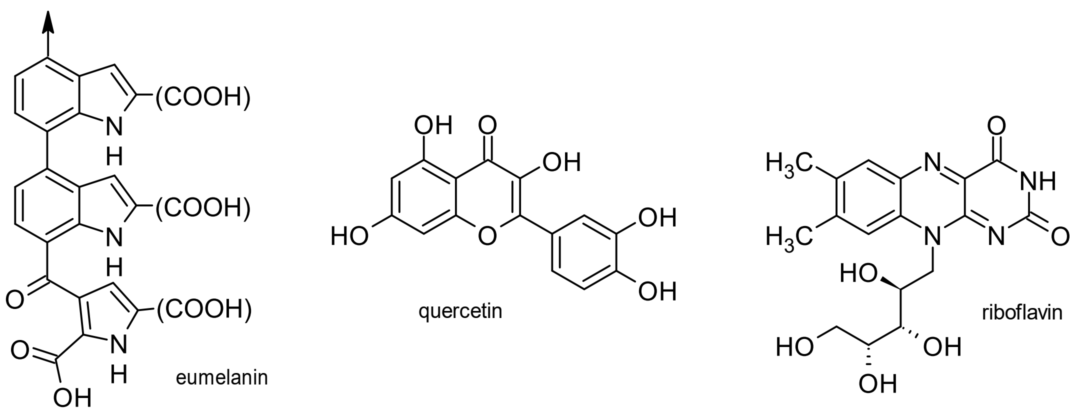

***Figure 3**:* Structures of eumelanin, quercetin and riboflavin.

4. Design an edible rechargeable battery from everyday food

In 2023, researchers at the Istituto Italiano di Tecnologia (IIT) designed the first fully edible and rechargeable battery. Their study, published in the journal *Advanced Materials* (Adv. Mater.), showed a battery made entirely from organic materials found in everyday food[23]. This electrochemical cell (Figure 4) is made up of a cathode containing several elements, such as quercetin (Figure 3), a natural antioxidant found in capers and buckwheat, which improved the stability of the cathode. For the anode, the researchers used riboflavin (also called vitamin B2, Figure 3), found in mackerel or almonds. Then, to promote ionic transfer between the electrodes, an aqueous solution was added as the electrolyte ($NaHSO_4aq$). Activated charcoal is also used to improve the electrical conductivity of the device, and nori algae separate the two electrodes while allowing ions to pass through. Finally, the battery is covered with a protective layer of beeswax to protect the components from passing into the body and to maintain the cohesion of the different layers. This battery is capable of operating at 0.65 V while delivering a current of 48 mA for 12 minutes, and has a storage capacity of 7.2 mA h g^{-1}. Although this performance is lower than that of commercial batteries, it offers a major advantage in terms of biodegradability and *in vivo* safety. This makes the device particularly suitable for medical applications. The battery has a rechargeability of 18 to 100 cycles, with variability depending on conditions of use.

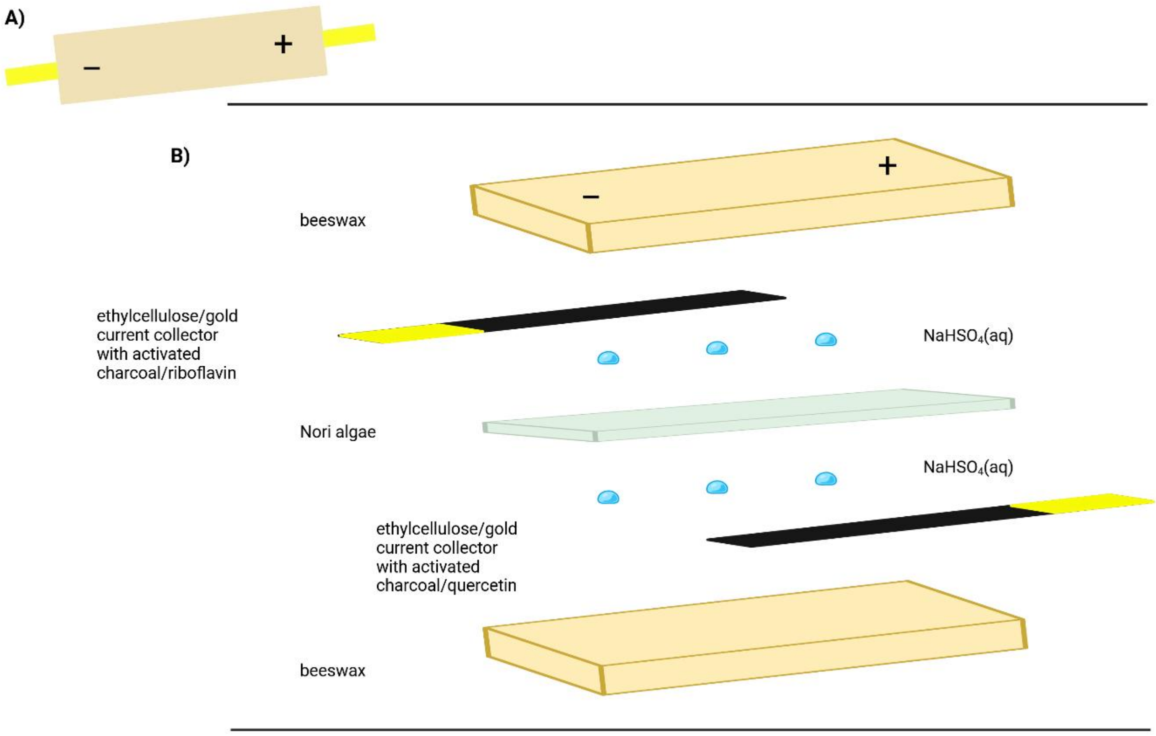

***Figure 4**:* Multi-layer composition of a battery made from food-grade materials.
A) General view of the battery. B) Ingredients used for each layer (Created with BioRender.com).

A 100% biodegradable battery, known as BioPower cell, was developed using organic materials and no critical metals (lithium, cobalt, nickel)[24]. Once out of service, it can be used as fertilizer, reducing waste by 50%, energy costs by 80% and CO_2 emissions by 60%. Biopower cell won the Green Product Award 2025[24].

Singaporean startup Flint is developing a rechargeable paper battery made from vegetable cellulose, a hydrogel electrolyte, and recyclable metals (zinc-manganese). It has an energy density of 226 W h kg^{-1}, is flexible, safe (non-flammable), and 100% biodegradable in six weeks[25].

Thanks to the use of natural ingredients, a new era is opening up in the design of miniature, rechargeable, eco-compatible, and edible batteries, which also avoid poisoning by ingestion[26]. The healthcare sector is very interested in this revolutionary approach[27].

5. Conclusion

From A. Volta to J.F. Daniell, via Wilhelm Josef Sinsteden (1803-1895), A.C. Becquerel, William Hyde Wollaston (1766-1828), Charles Féry (1865-1935), Georges Leclanché (1839-1882), G. Planté, and Nikola Tesla (1856-1943), many scientists and manufacturers have been crucial in the whole chain of inventions that have led to the production, storage, and use of electrical energy[17]! In 2025, electrical energy remains a key focus for researchers. Over the coming decades, the development of new miniaturized, environmentally friendly, and edible batteries will enable us to reach a new milestone in the diagnosis, and treatment of many diseases. As a result, other promising work is currently being carried out, again using bio-sourced materials such as gelatin[28], corn[29], and algal polymers[30]. The triboelectric effect can be an additional option for designing a nanogenerator[31]. Avoiding the use of (toxic) metals in battery design is a particularly interesting goal for scientists and physicians[32,33]!

The year 2025 also marks the 250th anniversary of the birth of A.-M. Ampère. This French scientist, called the “Newton of electricity” by James Clerk Maxwell, is the father of electrodynamics. His work was made possible by the development of batteries (primarily that of Wollaston). To the long list of scientists (e.g., Georg Ohm, M. Faraday, J.C. Maxwell, Joseph John Thomson, Wilmhelm Roentgen) who contributed to the study of electricity, magnetism, and light, we can even add Albert Einstein, who worked on Ampère's theory of molecular currents[34,35]. The genuine version of the Einstein-de Haas experiment apparatus has been found and is exhibited at the museum Ampère (Poleymieux-au-Mont d’Or, France)[36,37]. This is the only experimental work carried out by A. Einstein in 1915. Since 1799, batteries have become indispensable devices in the lives of people on Earth, and improving Volta's device remains a major concern for researchers today.

Acknowledgements

Marc Le Borgne would like to thank “Institut Convergence”PLAsCAN (ANR-17-CONV-0002). Marina Le Borgne would like to thank “La Région Auvergne-Rhône-Alpes” for obtaining the 2024 Merit Scholarship. The authors would like to thank Christine Janssen for editing the manuscript.

Data Availability Statement:

Not applicable.

References

1. Eurostat. Waste statistics - recycling of batteries and accumulators [internet]. 2024 [cited 2025 Sep 7]. Available from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_recycling_of_batteries_and_accumulators.
2. EUR-lex. Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC [internet]. 2018 [cited 2025 Sep 7]. Available from: https://eur-lex.europa.eu/eli/dir/2006/66/oj.
3. Iddan G, Meron G, Glukhovsky A, Swain P. Wireless capsule endoscopy. Nature. 2000;405(6785):417. doi:10.1038/35013140.
4. Qureshi W.A. Current and future applications of the capsule camera. Nat Rev Drug Discov. 2004;3(5):447–50. doi:10.1038/nrd1385.
5. Kutbee AT, Bahabry RR, Alamoudi KO, Ghoneim MT, Cordero MD, Almuslem AS, et al. Flexible and biocompatible high-performance solid-state micro-battery for implantable orthodontic system. npj Flex Electron. 2017;1:7. doi:10.1038/s41528-017-0008-7.
6. Doosthosseini M, Ghods H, Talkhoncheh MK, Silberberg JL, Weininger S. Hybrid cathode lithium battery discharge simulation for implantable cardioverter defibrillators using a coupled electro-thermal dynamic model. Cardiovasc Eng Technol. 2023;14(4):534–43. doi:10.1007/s13239-023-00676-0.
7. Ballardini G, Tamadon I, Guarnera D, Al-Haddad H, Iacovacci V, Mariottini F, et al. Controlling and powering a fully implantable artificial pancreas refillable by ingestible pills. Annu Int Conf IEEE Eng Med Biol Soc. 2023;2023:1–7. doi:10.1109/EMBC40787.2023.10340006.
8. Srinivasan SS, Alshareef A, Hwang A, Byrne C, Kuosmanen J, Ishida K, et al. A vibrating ingestible bioelectronic stimulator modulates gastric stretch receptors for illusory satiety. Sci Adv. 2023;9(51):eadj3003. doi:10.1126/sciadv.adj3003.
9. Li L, Li D, Wang Y, Ye T, He E, Jiao Y, et al. Implantable zinc-oxygen battery for in situ electrical stimulation-promoted neural regeneration. Adv Mater. 2023;35(32):e2302997. doi:10.1002/adma.202302997.
10. Traverso G, Finomore Jr V, Mahoney III J, Kupec J, Stansbury R, Bacher D, et al. First-in-human trial of an ingestible vitals-monitoring pill. Device. 2023 Nov;1(5):100125. doi:10.1016/j.device.2023.100125.
11. Huang HW, Chai PR, Lee S, Kerssemakers T, Imani A, Chen J, et al. An implantable system for opioid safety. Device. 2024 Oct;2(10):100517. doi:10.1016/j.device.2024.100517.
12. Volta A. On the electricity excited by the mere contact of conducting substances of different kinds. In a letter from Mr. Alexander Volta, F. R. S. Professor of Natural Philosophy in the University of Pavia, to the Rt. Hon. Sir Joseph Banks Bart. K. B. P. R. S. Philos Trans R Soc. 1800;90(part 2):403–31. Available from: https://archive.org/details/11Volta/mode/2up.
13. Laboratoire national de métrologie et d'essais. The international system of units (SI) [internet]. 2025 [cited 2025 Sep 7]. Available from: https://www.lne.fr/en/learn-more/international-system-units-si.
14. Oersted HC. Experiments on the effect of a current of electricity on the magnetic needles. Ann Philos. 1820;16:273-77. doi:10.1515/9781400864850.417.
15. Hofmann JR. Ampere, Electrodynamics, and experimental evidence. Osiris. 1987;3(1):45–76. doi:10.1086/368661.
16. Al-Khalili J. The birth of the electric machines: a commentary on Faraday (1832) 'Experimental researches in electricity'. Phil Trans R Soc A. 2015;373:20140208. doi:10.1098/rsta.2014.0208.
17. Root M. The TAB battery book: An in-depth guide to construction, design, and use. 1st ed. New York: McGraw-Hill; 2011.
18. Boulabiar A, Bouraoui K, Chastrette M, Abderrabba M. A historical analysis of the Daniell cell and electrochemistry teaching in French and Tunisian textbooks. J Chem Educ. 2004;81(5):754. doi:10.1021/ed081p754.
19. Kurzweil P. Gaston Planté and his invention of the lead-acid battery - The genesis of the first practical rechargeable battery. J Power Sources. 2010;195(14):4424–34.

doi:10.1016/j.jpowsour.2009.12.126.
20. Environmental Fact Sheet. HW-23: All about batteries. 2024 [cited 2025 Sep 7]. Available from: https://www.des.nh.gov/sites/g/files/ehbemt341/files/documents/2020-01/hw-23.pdf.
21. Kim YJ, Wu W, Chun SE, Whitacre JF, Bettinger CJ. Biologically derived melanin electrodes in aqueous sodium-ion energy storage devices. Proc Natl Acad Sci U S A. 2013;110(52):20912–7. doi:10.1073/pnas.1314345110.
22. American Chemical Society. Battery you can swallow could enable future ingestible medical devices [internet]. 2016 [cited 2025 Sep 7]. Available from: https://www.acs.org/pressroom/newsreleases/2016/august/battery-you-can-swallow-could-enable-future-ingestible-medical-devices.html.
23. Ilic IK, Galli V, Lamanna L, Cataldi P, Pasquale L, Annese VF, et al. An edible rechargeable battery. Adv Mater. 2023;35(20):e2211400. doi:10.1002/adma.202211400.
24. Northumbria University Newcastle. Global recognition for groundbreaking green battery technology [internet]. 2025 [cited 2025 Sep 7]. Available from: https://newsroom.northumbria.ac.uk/pressreleases/global-recognition-for-groundbreaking-green-battery-technology-3389282.
25. Material District. Sustainable paper battery: A new approach to energy storage [Internet]. 2025 [cited 2025 Sep 7] Available from: https://materialdistrict.com/article/sustainable-paper-battery-a-new-approach-to-energy-storage/.
26. Hui ML, Ng JH. First case of nickel-metal hydride battery ingestion in child. J Surg Case Rep. 2023;2023(5):rjad079. doi:10.1093/jscr/rjad079.
27. Pu Y, Wei W, Li S, Long J, Gu Y, Hong G, et al. Edible batteries for biomedical innovation: advances, challenges, and future perspectives. Chem Commun (Camb). 2025;61(46):8294–313. doi:10.1039/d5cc01385b.
28. Chen HY, Keller AG, Conn AT, Rossiter JM. GelBat: An edible gelatin-based battery. In 2023 IEEE 6th International Conference on Soft Robotics (RoboSoft). Institute of Electrical and Electronics Engineers (IEEE). 2023. (IEEE International Conference on Soft Robotics (RoboSoft)). doi:10.1109/RoboSoft55895.2023.10121947.
29. Contreras-Pereda N, Galli V, Cataldi P, Annese VF, Coco G, Athanassiou A, et al. A corn-based electrically conductive glue for integration of edible electronics. Small Sci. 2024;5(1):2400373. doi:10.1002/smsc.202400373.
30. Grira S, Alkhedher M, Abu Khalifeh H, Ramadan M, Ghazal M. Using algae in Li-ion batteries: A sustainable pathway toward greener energy storage. Bioresour Technol. 2024;394:130225. doi:10.1016/j.biortech.2023.130225.
31. Panda S, Hajra S, Kim HG, Achary PGR, Pakawanit P, Yang Y, et al. Sustainable solutions for oral health monitoring: Biowaste-derived triboelectric nanogenerator. ACS Appl Mater Interfaces. 2023;15(30):36096–106. doi:10.1021/acsami.3c04024.
32. Liao J, Liu Y, Yi J, Li Y, Li Q, Li Y, et al. Gut microbiota disturbance exaggerates battery wastewater-induced hepatotoxicity through a gut-liver axis. Sci Total Environ. 2022;809:152188. doi:10.1016/j.scitotenv.2021.152188.
33. Le Borgne M, Le Borgne M, Sossou-Echavidre K, Janssen C. To be or not to be manipulated by our bacteria? DRem. 2024;1(1):25–38. doi:10.71116/vj4jx563.
34. Einstein A. Experimenteller Nachweis der Ampereschen Molekularströme (in german). *Die Naturwissenschaften* 1915;3:237–8.
35. Janssen C, Le Borgne M. Preuve expérimentale des courants moléculaires d'Ampère. Bull SAAMA 2024:26–8 [French translation of the original article by A. Einstein, Experimenteller Nachweis der Ampereschen Molekularströme (in german). *Die Naturwissenschaften* 1915;3:237–8].
36. San Miguel A, Pallandre B. Revisiting the Einstein-de Haas experiment: the Ampère Museum's hidden treasure. Europhys News. 2024;55(4):28–31. doi:10.1051/epn/2024409.
37. Musée Ampère. Our labels [internet]. 2025 [cited 2025 Sep 7]. Available from: https://amperemusee.fr/en.