

UC Irvine

UC Irvine Previously Published Works

Title

Biobased materials for sustainable printed circuit boards

Permalink

<https://escholarship.org/uc/item/0191n3jz>

Journal

Nature Reviews Materials, 7(10)

ISSN

2058-8437

Authors

Ogunseitan, Oladele A
Schoenung, Julie M
Lincoln, Johnny
et al.

Publication Date

2022-10-01

DOI

10.1038/s41578-022-00485-2

Peer reviewed



Biobased materials for sustainable printed circuit boards

Oladele A. Ogunseitan^{1,2}✉, Julie M. Schoenung^{2,3}, Johnny Lincoln², Bichlien H. Nguyen⁴, Karin Strauss⁴, Kali Frost⁴, Eric Schwartz³, Haoyang He³ and Maryam Ibrahim⁵

Electronic waste, with printed circuit boards (PCBs) at its heart, is the fastest-growing category of hazardous solid waste in the world. New materials, in particular biobased materials, show great promise in solving some of the sustainability and toxicity problems associated with PCBs, although several challenges still prevent their practical application.

Initiatives to circularize the economy of electronic products by increasing the use of environmentally sustainable, recyclable and less toxic materials have been difficult to implement. Among the reasons are the incremental progress in developing electronics design focused on issues such as resource scarcity and the lack of strong regulatory incentives for developing new criteria for product performance (for example, including longevity and ease of repair) and responsible stewardship of materials used (for example, including lower carbon emissions and reduced toxicity)¹. The situation is compounded by the hazardous post-consumer waste linked to the electronics industry².

Effective remedies will require research that integrates strategies for improving product design, expanding the technical infrastructure needed to recover and recycle valuable resources, establishing enforceable regulatory policies for environmental protection, and discovering naturally safer materials and processes with smaller environmental footprint. Such integration will drive innovation towards a sustainable and increasingly circular economy of electronic products.

In this Comment, we explore opportunities for the use of biobased materials — materials derived from non-fossil natural resources such as cultivated plants, microorganisms and agricultural waste — in electronic products and strategies to overcome challenges in scaling their adoption. We focus on printed circuit boards (PCBs) as a common constituent of new electronic products and e-waste streams, recognizing that changes in their design and manufacture can have a transformative influence throughout the industry.

Towards sustainable PCBs

PCBs are ubiquitous in consumer and industrial electronic products, representing the world's 84th most traded product, and were projected to be worth more than US\$60 billion in 2022. Commercial PCBs are

based on synthetic polymers conventionally derived from unsustainable resources and usually incorporate toxic chemicals, including halogenated flame retardants. PCBs are typically made of woven fibreglass cloth with a flame-retardant epoxy resin matrix (FR4). Synthetic polyimide, Teflon, polyester laminates, cyanate ester and ceramics are selectively used for various applications. The material composition, physical size, component assembly and design specifications vary widely according to device function, performance, sturdiness, reliability and production cost, each of which independently or collectively may influence the potential for recyclability, resource recovery and pollution hazards posed during manufacturing, end-of-life, materials recovery and waste management operations³.

The most common commercially produced PCBs are multi-layer varieties that have relatively high concentrations of valuable metals (up to 180,000 g ton⁻¹ Cu, 600 g ton⁻¹ Ag and 80 g ton⁻¹ Au), making them attractive to electronic waste recyclers and urban miners⁴. However, globally, less than 20% of used PCBs are collected for recycling. Most scalable methods for recovering valuable materials from PCBs are costly, inefficient, rely on poorly designed collection systems and generate toxic by-products. Commercial PCBs have not traditionally been designed with consideration for environmental impacts at the end of their functional life: circular economy principles demand a different set of priorities, including the use of materials from circular sources or discarded resources, and methods that allow easier separation of materials.

Demonstration projects have shown that the use of materials such as paper, flax and biobased resin matrices in prototype PCBs can reduce the environmental impacts of source materials and improve recovery and reuse of metals and electronic components, minimize the use of toxic flame retardants, and provide pathways for safer end-of-life management^{5–7}. Ensuring high-level

¹Department of Population Health and Disease Prevention, University of California, Irvine, Irvine, CA, USA.

²World Institute for Sustainable Development of Materials (WISDOM), University of California, Irvine, Irvine, CA, USA.

³Department of Materials Science and Engineering, University of California, Irvine, Irvine, CA, USA.

⁴Microsoft Research, Redmond, WA, USA.

⁵Department of Environmental and Occupational Health, University of California, Irvine, Irvine, CA, USA.

✉e-mail: Oladele.Ogunseitan@uci.edu

<https://doi.org/10.1038/s41578-022-00485-2>

performance and long-term reliability for such biobased substrates has proven elusive, in part because of technical challenges associated with their tendency to retain moisture⁸. Biobased materials engineering for PCBs is still in its infancy, but the electronic industry's excitement about circular economy is stimulating new lines of research and we believe that with the right level of investment in development and scale-up, they can match the performance of traditional synthetic substrates within the next decade.

A transition to biobased materials in PCBs would reduce not only their toxicity but also the energy requirements associated with their manufacturing and end-of-life management. A cradle-to-gate analysis of the carbon emissions footprint of conventional PCBs, covering raw material extraction, manufacturing and transportation, concluded that improvements in the electricity consumption during manufacturing and the use of greener materials are essential for reducing the product's carbon footprint⁹. Moreover, a review of the carbon footprint of bio-composite materials for sustainable products noted that despite data gaps and uncertainties, including assumptions about the geographical location of raw materials and land use practices, researchers have consistently reported a reduction of up to 16% in greenhouse gas emissions when switching from, for example, fibreglass to biobased composite materials¹⁰.

Challenges remain in the use of life-cycle impact assessment (LCIA) tools for supporting the decision to adopt biobased materials instead of synthetic polymers for PCBs, including the definition of categories of biobased materials. For instance, the US Food and Drug Administration's definition of bioplastics includes products made with petroleum-based polymeric matrices blended with natural fibres, which may not be susceptible to full biodegradation in environmental contexts and may not meet sustainability specifications. It is also necessary to investigate the potential of such polymers to interact with metallic and organic chemical components in PCBs in ways that require new infrastructure for safe post-consumer resource recovery and e-waste management.

Finally, it is critical to consider the other current uses of biobased materials to avoid competition with food, clothing and biofuel resources, which may exacerbate environmental justice issues such as equitable access to essential resources. Such considerations lead us to argue strongly for prioritizing agricultural waste as source material for biobased PCBs and using comparative

LCIA to identify potential trade-offs associated with their adoption and scale-up.

Converging drivers of innovation towards sustainability

Research has intensified to identify better ways to collect and recycle PCBs based on fossil polymers, driving technical innovation towards circularity. Sustainable circularity will require more research to discover high-performance biobased polymers for replacing synthetic polymers in PCBs. Other influential drivers to support the transition include regulatory policies and incentives, including, for example, consideration of sustainable materials in electronic performance standards, such as the [EPEAT Ecolabel](#) administered by the Global Electronics Council. The convergence of policy initiatives to encourage extended product responsibilities and to stimulate consumer participation in domestic waste management initiatives will also likely contribute to the rapid advance of transformative projects to completely circularize the materials economy of electronic products.

1. Awasthi, A. K., Li, J., Koh, L. & Ogunseitan, O. A. Circular economy and electronic waste. *Nat. Electron.* **2**, 86–89 (2019).
2. Ogunseitan, O. A., Schoenung, J. M., Saphores, J.-D. M. & Shapiro, A. A. The electronics revolution: from e-wonderland to e-wasteland. *Science* **326**, 670–671 (2009).
3. LaDou, J. Printed circuit board industry. *Int. J. Hyg. Environ. Health* **209**, 211–219 (2006).
4. Ribeiro, P. P. M., dos Santos, I. D. & Dutra, A. J. B. Copper and metals concentration from printed circuit boards using a zig-zag classifier. *J. Mater. Res. Technol.* **8**, 513–520 (2019).
5. Kosbar, L. L., Gelorme, J. D., Japp, R. M. & Fotorny, W. T. Introducing biobased materials into the electronics industry. *J. Ind. Ecol.* **4**, 93–105 (2000).
6. Nassajfar, M. N., Deviatkin, I., Leminen, V. & Horttanainen, M. Alternative materials for printed circuit board production: an environmental perspective. *Sustainability* **13**, 12126 (2021).
7. Bharath, K. N. et al. A novel approach for development of printed circuit board from biofiber based composites. *Polym. Compos.* **41**, 4550–4558 (2020).
8. Lincoln, J. D., Shapiro, A. A., Earthman, J. C., Saphores, J. M. & Ogunseitan, O. A. Design and evaluation of bioepoxy-flax composites for printed circuit boards. *IEEE Trans. Electron. Packaging Manuf.* **31**, 211–220 (2008).
9. Yung, W. K., Muthu, S. S. & Subramanian, K. in *Environmental Carbon Footprints* 365–431 (Butterworth-Heinemann, 2018).
10. Correa, J. P., Montalvo-Navarrete, J. M. & Hidalgo-Salazar, M. A. Carbon footprint considerations for biocomposite materials for sustainable products: a review. *J. Clean. Prod.* **208**, 785–794 (2019).

Acknowledgements

The authors acknowledge support from Microsoft Research and the Lincoln Dynamic Foundation World Institute for Sustainable Development of Materials (WISDOM) at the University of California, Irvine. They thank A. Pistoia, Waste and Circular Economy Program Manager at Microsoft, for providing feedback on the draft version of this article.

Competing interests

J.M.S. and spouse have equity interest in Microsoft Corporation. The relationship with Microsoft has been reviewed and approved by the University of California, in accordance with its conflict-of-interest policies. B.H.N., K.S. and K.F. are employees of Microsoft Corporation. O.A.O., J.L., E.S., H.H. and M.I. declare no competing interests.