Research team proposes innovative wearable e-textiles for a sustainable circular economy

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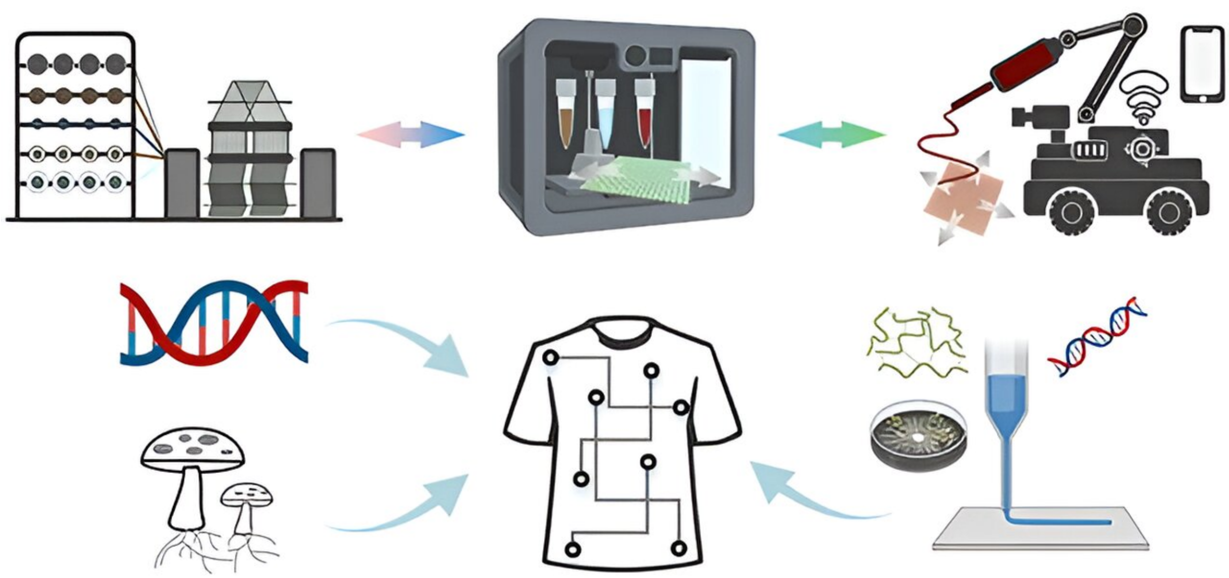

Illustration showing the marriage of 4R concepts with functional fibre production/digital additive manufacturing and biofabrication techniques. Credit: Dr Harvey Shi

If electronic textiles (e-textiles) are to have a sustainable future and at scale, then a transition is needed to unlock innovative wearable e-textiles that fit a sustainable circular economy—adopting what has been termed as the 4R design concept: repair; recycle; replace; reduce.

E-textiles are worn close to and/or against the surface of the skin, with applications in health care, gaming, athletic training and environmental monitoring. Thanks to embedded electronic components, e-textiles can store and harvest energy, sense, display, actuate and compute.

Yet there are two major challenges to the future growth of e-textiles: first, high costs, therefore resulting in slower consumer adoption. Second, high environmental costs associated with mass production, in particular, microplastic water pollution. Fundamentally, we need new ways to prevent the scale-up of e-textiles from becoming the next electronic waste (e-waste) environmental fiasco.

This is according to a team of engineers and scientists from the U.K., Canada, the U.S. and China, led by the University of Cambridge, who warn that the e-textile supply chain and its potential for scalable commercialization could be "further complicated" by the associated global environmental burden, and the growing use of nanomaterials in e-textiles. They say that some of these nanomaterials can pose environmental challenges and could also have adverse effects on human health (e.g., skin irritation and/or absorption of loose nanoparticles into the skin).

Writing in the journal *Nature Materials*, the research team proposes the 4R e-textile design concept (repair; recycle; replace; reduce) alongside innovations in materials selection and biofabrication-inspired processing—a revolutionary approach that uses additive manufacturing processes to produce biomaterials, devices, cells and tissues. The aim is to reach sustainable growth and balance economic returns/scalable commercialization with "environmental consciousness," at a time when consumers are actively aligning their purchasing behaviors with sustainability goals.

The 4Rs for more affordable, versatile e-textiles products and enhanced supply chains have been defined as follows:

Repair

"Fiber level" repairs, such as resewing, reweaving, reknitting and self-healing of electronic fibers, and bulk "fabric-level" repairs, such as recoating, reprinting and respraying of active materials.

Eventually, the e-textile materials would adopt self-healing mechanisms, which would give them the capability of self-repair over time. Also, with a modular approach to future e-textile designs, it is also possible to switch out faulty components easily and rejuvenate the electronic functionalities of the system.

Recycle

In the near term, recycling can be encouraged by categorizing and separating e-textiles components into the base textile and the electronic modules.

The base textile can be recycled as regular clothing and the electronic components recycled as regular e-waste streams.

However, e-textile recycling becomes more complex when the fabrics contain, for example, functionalized electronic fibers with electrical conductivity and sensing capabilities. Extraction in most cases would be time-consuming and costly, say the researchers, so reusing and repurposing used functional components might be a viable option.

Replace

The research team also notes that while biomass fibers such as those extracted from wool, silk, cellulose, flax and hemp, could provide a renewable source for e-textile production, this is not often possible. This is due to the fact that nano- and microstructured active coatings and functionalized strategies need to be applied to enable electronic functions, that would otherwise be missing. Therefore, novel materials design that utilizes earth-abundant elements can accelerate e-textile commercialization and make them more cost-effective for the average consumer.

Additionally, the research team also calls for alternative bioderived material options for electronic fiber encapsulation to create non-irritating and skin-compatible e-textile surfaces. Currently, material options are mostly synthetic and non-biodegradable.

Reduce

This, according to the researchers, can be interpreted in two ways:

- Reducing the total emissions and energy consumption during e-textile production and deployment.
- Reducing the total amount of material used in e-textiles to achieve and maintain a specified function.

"Currently, the scalable commercialization of e-textiles products is limited by high pricing and lack of diversity, durability and washability," said co-lead author Professor Shery Huang from Cambridge's Department of Engineering. "This is why materials considerations in the 4R realm (identified as repair; recycle; replace; reduce) need to be addressed in order to secure a sustainable future for e-textiles development."

"Machine washing of e-textiles has, to date, contributed to an increase in microplastic pollution in the water stream. The challenge here is to reinforce the functional longevity of e-textiles, while minimizing the number of microparticles released. Strategies for this include the decoupling of transient/single-use components or designing 'dry' or 'vapor-based' cleaning protocols that consume less water," said co-lead author Dr. Harvey Shi from Western University, Canada.

The research team has proposed various sustainable e-textile strategies. For example, an e-textile can be divided as "canvas" and "modules" components. The "canvas" is machine-washable and provides the bulk of the user's sensory experience, while the "modules" are the interconnected components that carry electronic functionalities.

The researchers say that the "canvas" should be designed to maintain reliability as an electrically insulating and chemically inert medium under persistent use and occasional reconfiguration. The "modules" meanwhile, can be designed with various formats to be easily removable and replaceable, so that their electronic functions can be maintained for long-term use.

The "canvas" and "modules" can be sorted by three preliminary lifespan ratings: quasi-permanent, with a lifespan of approximately one year; multiple use, with a lifespan ranging from weeks to months; and single-use.

According to the researchers, the timeline for 4R-integrated e-textiles development can be broken down into the following:

In the near term—standardizing e-textiles platforms to integrate a variety of electronic modules, leading to innovative processing technologies and industrial standardization that will bring affordable e-textiles to a broader consumer base.

Further developments include: automated assembly processes; a database of functional ink formations for e-textiles developers to use; and establishing standardization in component decoupling based on longevity ratings—a move that also effectively minimizes the release of electronic micro- or nanoparticles into the water stream.

Yifei Pan, Ph.D. student in the Biointerface Research Group at Cambridge, said, "Adopting this standardization approach in the near term can enable developers to create a customized array of cross-compatible functional components; reinforce user safety and public interests in the personalized health care and customized non-invasive therapeutics market (i.e., product certification); and can lead to designated cleaning protocols."

In the mid-term—employing user-centric design strategies and innovative processing technologies to offer a broader range of e-textiles to the public, ones that are comfortable to wear and which can be personalized to the user.

"This is the point at which self-healing/self-repairing fibers can be achieved through molecular design and without the need for human intervention," said Dr. Shi. "This would effectively create a repairable e-textile ecosystem, in which the product can be readily disassembled and refurbished without adding to the environmental burden."

In the long term—sustainable and "living" e-textiles can be realized, such as engineered robotic skin. Biohybrids, fiber-on-demand and biofabrication technologies will enable these e-textiles to self-clean (thus minimizing the requirements for machine washing or solvent-based cleaning), self-repair and be capable of self-regeneration in the future.

"In summary, the road towards 'green,' biohybrid and circular fabrication calls for the marriage of our 4R concepts with functional fiber production/digital additive manufacturing and biofabrication to produce highly customizable e-textile designs," said Professor Tawfique Hasan from the Cambridge Graphene Center.

Professor Huang added, "As we drive towards future sustainable e-textile manufacturing, there could be a paradigm shift from a centralized mass production strategy with one principal facility to a more widespread additive manufacturing/3D printing platform—ultimately creating and repairing e-textiles on-site."

More information: HaoTian Harvey Shi et al, Sustainable electronic textiles towards scalable commercialization, *Nature Materials* (2023). DOI: 10.1038/s41563-023-01615-z

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