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Integrating environmental assessment into early-stage wearable electronics research

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This perspective explores the intersection between technology research and environmental assessment during the early-stage development of next-generation wearable electronics, encompassing flexible, stretchable, soft, transient, printed, and hybrid electronics. While significant advancements have been made in the development of high-performance materials, fabrication processes, and device engineering for wearables, their environmental performance is often overlooked. Even when environmental claims for new materials or processes are stated, they are often made without any quantifiable justification. This perspective critically analyses current approaches at assessing environmental performance during the early research stage and recommends how and when to integrate an environmental assessment to ensure both high device functionality and environmental performance. The timeliness of this perspective arises from the urgent need to address environmental concerns in the rapidly expanding wearable electronics research field and commercial use, which is projected to grow exponentially in the coming decade. Research in wearable electronics is multidisciplinary, involving material science, chemistry, physics, biology, electrical engineering, medicine and neuroscience. This perspective recommends timely integration of relevant environmental assessment efforts, including life cycle assessment, into this multidisciplinary mix, thereby ensuring that next-generation wearable electronics are aligned with sustainable development policies and regulatory systems.

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1. Introduction

In the era of the Internet-of-things (IoT), a projected 1 trillion electronic devices are expected to be in operation by 2035,[1] with wearables representing a significant share.[2] Many of these wearable devices can benefit society,[3] for example by monitoring, regulating, and/or actuating parameters of impact for the environment,[4] well-being,[5] healthcare,[6] agriculture (plant wearable sensors),[7] and for soft robotics targeting advance manufacturing[8] (Fig. 1a). Next-generation wearable devices are distinct from their current commercial counterparts (*e.g.*, earphones, hearing aids, smart watches, or fitness trackers) and require innovation in materials that are mechanically compliant (*e.g.*, soft, flexible, stretchable), while maintaining electronic function when they interface with the human body, plants, or soft robots. They need to conform easily onto any surface depending on their spatial environment to minimise the mechanical mismatch between the device and user (Fig. 1b). This ensures comfort, avoids delamination during use, and reduces the risk of foreign-body response when implanted inside the body, especially for chronic use.[9] Furthermore, mechanical flexibility is a key enabler of scalable, high-volume manufacturing methods such as roll-to-roll, flexographic and gravure printing.[10] Similarly, flexible hybrid electronics leverages the high-performance computing of silicon integrated circuits with the use of flexible materials and printing techniques to manufacture compliant large-area electronics.[11] The rapid rise of next-generation wearables has ushered in a new era of technological innovation, yet it also comes with concerns.

A critical dilemma facing researchers performing early-stage innovation of wearable technology is: when and how should environmental assessments be integrated into the research process? (Fig. 1c). Early-stage material and device research for wearables often prioritize performance, functionality and scalability over environmental sustainability. When sustainability claims for new materials or processes are stated, they are often made without any quantifiable justification.[12–18] Despite an increasing trend in the number of publications in wearable electronics with a sustainability focus over the decades, the assessment of their environmental impact is lagging behind (Fig. 1d).

This is problematic considering the environmental and resource challenges observed for conventional electronics in the past, such as the massive generation of non-recycled electronic waste (e-waste),[19] the use of scarce metal resources (such as silver, tin, and tantalum),[20] and the use of toxic materials such as lead,[21] polychlorinated biphenyls,[22] and perfluoroalkyl substances (PFAS).[23] Furthermore, petroleum-based polymers used as encapsulation materials for wearables, such as silicone, polyurethane (PU) and styrene-based elastomers are persistent and non-renewable.[24] These lessons point to a need for considering environmental and resource aspects when developing next-generation wearables electronics which are shifting towards environmentally friendly and circularity-driven innovations.[25] Addressing this requires deeper collaboration between experimental technology researchers with environmental experts, particularly those skilled in life cycle assessment (LCA) methodologies and systems-level sustainability thinking.

In addition, implementation of wearable electronics in our society fundamentally presumes widespread deployments of the technology following successful industrial upscaling. Regardless of whether this is achieved through spinout efforts or conducted in existing industry, companies are required to identify and manage risks associated with human health and the environment. In the European Union (EU), this is partly handled through several key regulatory systems, such as Critical Raw Materials Act,[26] REACH (Registration, Evaluation, Authorisation, and Restriction of Chemicals),[27] CSRD (Company Sustainability Reporting Directive)[28] and the EU Taxonomy.[29] Similar regulatory systems in the United States such as the Critical Minerals & Materials Strategy,[30] Japan's green growth strategy to support their 2050 carbon neutral goal,[31] and China's Green Development plan,[32] signifies the importance of assessing the environmental impact of emerging technologies.

Environmental assessment efforts, including LCA, is crucial for complying with these regulatory systems as it provides quantitative data needed to assess and report on the environmental impacts of products and processes throughout their entire lifecycle, from raw material extraction to end-of-life (EoL). Environmental assessment tools should be incorporated throughout the entire research pathway, *i.e.* from the formulation of the idea and hypothesis to publication of results and commercialisation (Fig. 1c). This will encourage researchers in wearable electronics to align their work to be relevant for, and significantly contribute to, sustainability and avoid conducting their research toward scientific sustainability 'dead ends'. Furthermore, making the scene even more complicated,

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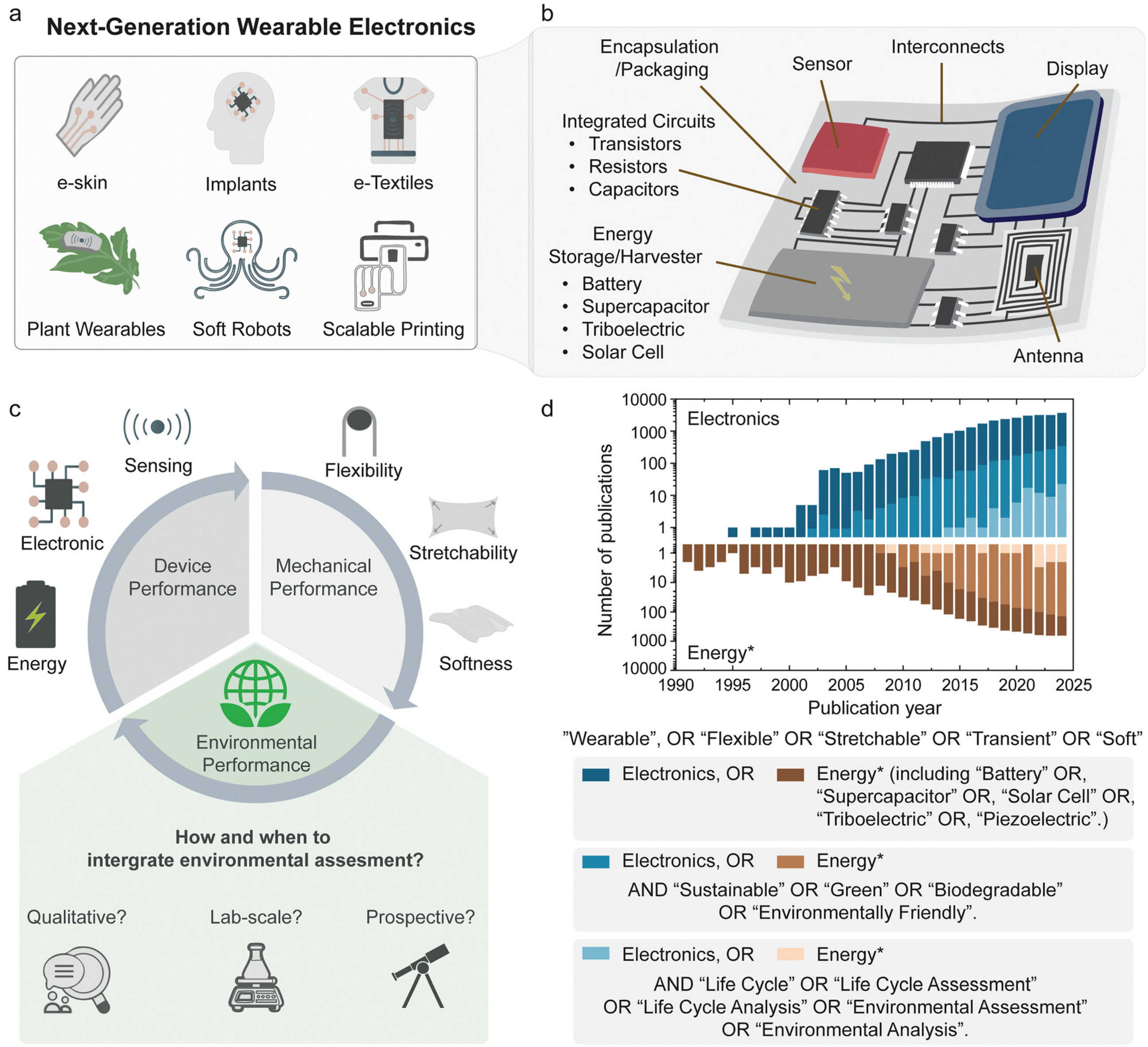

Fig. 1 Schematic representation of (a) next-generation wearables and (b) a representative device consisting of various electronic and energy components. (c) The key performance metrics of a wearable device and the challenge of assessing environmental performance. (d) Number of publications of wearable electronics and energy devices between 1990 and 2024 listed in the Web of Science as of 25/05/2025.

regulatory systems have been developed in the past, and will certainly continue in the future. Researchers should be aware of regulatory frameworks and how they continuously advance over time and what impact they have on *e.g.* LCA.

In this perspective, we first outline some important considerations when striving for high environmental performance (including also resource performance) in the research processes for wearable electronics. We then review previous attempts at integrating environmental aspects in the development of wearable electronics. Finally, based on the critical considerations and prior work, we recommend an approach for how environmental aspects can be successfully included at the early-stage research processes for wearable electronics.

2. Important environmental aspects for wearable electronics

Electronics, including wearable electronics, are complex systems and composites made from many different materials. They can cause environmental impacts during different stages of their life cycle, such as raw material extraction (*e.g.*, diesel use and emissions from mining tailings), manufacturing (*e.g.*, tailpipe emissions), the use phase (*e.g.*, electricity use), and end of life (*e.g.*, toxic emissions from landfill and incineration exhausts). Considering the important issue of e-waste, EoL considerations are particularly important not to omit. The emissions and resources extracted along the life cycle can

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furthermore cause various environmental impacts, such as climate change, toxicity impacts, and mineral resource scarcity. A life-cycle perspective is therefore important when evaluating the environmental performance of wearable electronics. LCA has been developed with the aim of assessing environmental and resource impacts of products holistically, considering complex global supply chains as well as various environmental and resource impacts.[33] LCA is generally regarded as the most well-developed method for assessing the environmental sustainability of products,[34] and has previously been applied to conventional electronic products, such as common consumer electronics (*e.g.*, mobile phones, laptops, watches).[35] Without a life-cycle perspective and the application of LCA during research and innovation of wearable electronics, there is a risk that a change to a seemingly more benign material in a specific wearable system causes higher impacts upstream. The importance of a life-cycle perspective has been pointed out specifically for organic electronics (which includes wearable applications) by McCulloch *et al.*, who emphasised the need for life cycle-based sustainability metrics like energy payback time (EPBT) and embedded carbon.[15]

When performing an LCA, a so-called functional unit needs to be defined (ISO 14040:2006).[36] It is a quantitative measure of the product's function, to which all upstream and downstream flows are related, and using the same functional unit is important in LCAs involving comparative assertions. Common functional units in LCA are 1 device, 1 kg, or some performance measure, like 1 person-km for vehicles. LCAs of conventional electronics often apply 1 device as a functional unit,[37] which is convenient and allows for analyses of environmental and resource hotspots but does not reflect the performance of devices. Identifying relevant performance-based functional units for wearable electronics is thus important to ensure useful comparisons between different technologies.

The selection of environmental impact categories is another important methodological choice in LCA. It is generally advisable to include multiple environmental impact categories in LCA to enable analyses of trade-offs,[38] thus going beyond single-indicator metrics like the carbon footprint. Broader lists of impact categories are available in "packages" of impact assessment methods, such as ReCiPe.[39] Particularly important impact categories for conventional electronics include global warming, energy requirement, mineral resource scarcity, (eco)-toxicity, pollution and generation of e-waste. Depending on the wearable electronic designs, these impact categories might be particularly relevant for wearable electronics as well.

Conventional electronics is an established – albeit rabidly changing – product category. Commercial wearables such as earphones, hearing aids, smart watches, or fitness trackers, do exist, but next-generation versions are characterized by radical novelty, fast growth, high uncertainty, and potentially high societal impact.[40] For emerging technologies at a currently immature state (*e.g.*, developed at laboratory scale), researchers and developers have high possibilities to change the design to improve the environmental performance. Therefore, performing LCA to guide the design of wearable electronics should preferably be done at such an early stage of development, since it enables researchers and developers to make informed decisions that align innovation with environmental performance. Without such early guidance, much effort can be spent on materials and device architectures that will later be revealed to have poor environmental performance.[18,41]

However, at this early stage, assessments of the technology as-is might be of limited relevance considering the notable changes it will likely undergo before reaching production volumes of environmental significance. Therefore, it is recommendable to apply a prospective perspective, which for the LCA modelling means that the product system is modelled "at a future point in time relative to the time at which the study is conducted".[42] For an emerging technology, a particularly relevant future time is when it has reached maturity, commercialization, and large-scale production, since it is at this point the environmental impacts of the technology will matter the most.

Unfortunately, the early stage of development is also when there is the least information about the technology, both in its current immature and future mature states, which can be referred to as the process design paradox (Fig. 2). The opportunity to influence a technology's environmental footprint is highest in the early design and material selection phases, when fundamental choices about materials, processing conditions, device architecture, and manufacturing routes are being decided. This is also when detailed knowledge of a design's environmental performance is least available, so traditional LCAs typically come only after a product is largely defined.[41] By then, making substantive changes for environmental performance may be technically or economically infeasible. This paradox makes it difficult to align environmental objectives with rapid innovation, since environmental guidance often arrives only after key decisions have been locked in. Thus, finding relevant data representing production, use and EoL in the future can be challenging. However, there are attempts at developing accurate upscaling approaches and thereby easing the design paradox. Examples of such upscaling approaches include chemical process simulations, process calculations, stoichiometric calculations, and using relevant large-scale processes as proxies.[43] Applying such upscaling approaches is particularly important to ensure fair comparisons with currently mature technologies.[44]

In addition, other technologies that are part of the wearable electronic product's life cycle might change before the time of commercialisation. For example, electricity generation is undergoing a rapid transition world-wide, with increasing shares of solar and wind power. Any product using significant amounts of electricity during its production or use will thus likely see altered environmental performance over time. Approaches to consider such changes in prospective LCA are under development. For example, the Premise tool can generate future versions of the LCA database Ecoinvent that follow scenarios from the Intergovernmental Panel on Climate Change,[45] meaning that, *e.g.*, electricity production at the future point in time (*e.g.*, 2040 or 2050) is changed according to those scenarios.

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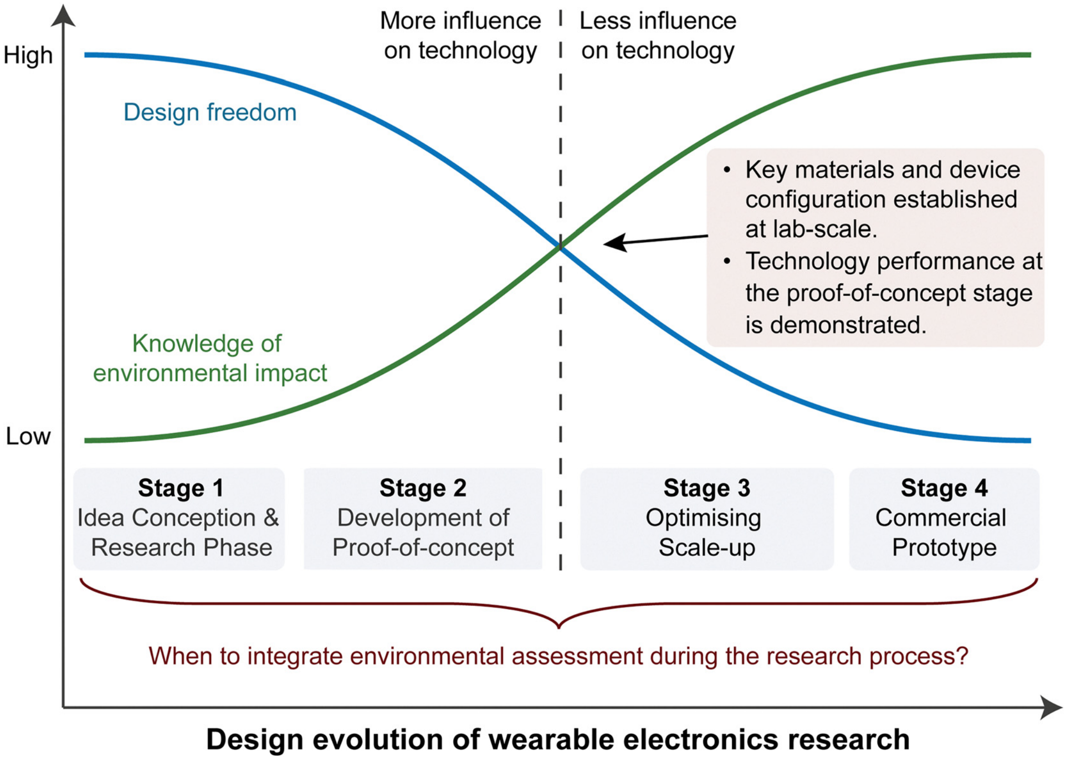

Fig. 2 An illustration of the process design paradox or the Collingridge dilemma in early-stage innovation of wearable electronics technology and its prospective environmental impact.

Consequently, important environmental considerations for early-stage wearable electronics research are to (i) apply a life-cycle perspective and LCA, (ii) assess environmental performance using relevant functional units, (iii) include several impact categories to analyse trade-offs, and (iv) have a prospective perspective to reveal the potential environmental performance of the wearable electronic product at commercialisation.

3. Examples of environmental considerations in wearable electronics research

To meaningfully improve the environmental performance of wearable electronics, it is essential to consider the hierarchical levels of a device. These levels include the full device design, including integrated circuits, displays, interconnecting conducting tracks, antennas, substrate/packaging, and the power source (*e.g.*, batteries, solar cells) to enable autonomous operation (Fig. 1b). Each level introduces distinct material choices, processing routes, and EoL considerations that collectively shape the device performance and its environmental impact. In this section, we highlight selected examples where environmental aspects have been considered at the device, component, and power-source levels. An overview of key examples discussed in this section is summarised in Table 1 for reports with in-depth and Table 2 without in-depth environmental assessments. We define "in-depth" assessments as examples with structured LCA in the lab-scale, while without referring to studies that make qualitative sustainability claims without structured methodology.

3.1. Device level

At the device level, a review by Luo *et al.* provided a roadmap for flexible sensors used in wearables and the IoT devices, which centred on scalable manufacturing and EoL strategies.[12] They underscore that both recyclability and biodegradability should be pre-integrated into future innovations of material/device architectures. Importantly, they spotlight the use of bio-derived packaging substrates that are designed to facilitate disassembly of the device for recycling of the internal electronic components or biodegradability for disposable single-use devices. The packaging material plays a key role in holding the electronic components together, especially under mechanical stress and acting as a protection layer of the internal components from moisture or oxygen. It is the first layer that must disintegrate before the internal components can be degraded further or be recycled at the EoL.[46] Below we have highlighted several key examples of integrating environmental considerations at the device level.

A "3R Electronics" method of resilient, repairable, and recyclable electronics by Tavakoli *et al.*, enabled mechanical disassembly and recycling of the internal electronic components of a wearable device.[47] The concept utilised the non-permanent physical crosslinks of the block-copolymer elastomer binder and substrate *via* solvent dissolution. However, this

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Table 1 Highlighted examples of studies of materials and devices with in-depth environmental assessments

Proof of concept	Innovation	Key materials	Mechanical properties	Quantitative environmental assessment approach	System boundaries	Functional unit	Impact categories	Ref.
Device-level								
OECT & OPD	Leaf skeleton reinforced electronics	Leaf skeleton, ethyl cellulose, chitosan, Ag, PEDOT:PSS	Flexible	Lab-scale LCA Impact categories: climate change	Cradle to gate	1 m^2 substrate	Climate change	76
E-textile	New eco-friendly e-skin with integrated sensor	Tencel™/Lyocell fabrics PEDOT:PSS, graphite, graphene	Flexible	Lab-scale LCA	Cradle to gate	10 cm × 1 cm surface	18 (all from the ReCiPe 2016 package)	77
Paper based circuit board	Processing technique for paper-based circuit boards	Paper, PU, Ag flakes, methyl acrylate	Flexible	Lab-scale LCA	Cradle to gate plus end of life	10 000 m^2 PCB	9 (from the CML package)	78
Energy storage and power source component-level								
Tribo-electric nanogenerator	Comparison between high & low efficiency modules and other energy harvesters	PTFE, acrylic sheet, Cu, Ti, Pb, ethanol & acetone	Flexible	Lab-scale LCA	Cradle to gate	1 m^2 module	11 plus weighted single-score	73
Battery	A transient Zn-ion battery with high cyclic stability	Zn, PDA, CMC, agarose, glutaraldehyde, $ZnSO_4$, dopamine, piperidine, activated charcoal, carbon black, carbon cloth, glycerol	Flexible	Lab-scale LCA	Cradle to gate	1 kWh energy storage capacity	18 (all from the ReCiPe 2016 package)	71
Battery	First LCA of all-organic battery	Graphite, pEP(QH_2)E, glass microfiber, pEP(NQ)E, biopolymer plastic & sulfuric acid	Flexible	Lab-scale LCA	Cradle to gate	3 cm × 3 cm cell and 1 kWh energy storage capacity	16 (from the ILCD package) plus weighted single-score	79
OPV & LED	Printed OPV made from recycled and biobased polymers	LiF, Ag, ITO, ZnO, histidine,biochar, P3HT:PCBM, PEDOT:PSS, PET, rPET & PLA	Flexible	Lab-scale LCA	Cradle to gate	1 m^2 solar cell area and 1 kWh produced	Climate change and cumulative energy demand	72

PTFE = poly(tetrafluoroethylene), PDA = polydopamine, CMC = carboxymethyl cellulose, pEP(QH_2)E = poly(3,4-ethylenedioxythiophene 3,4-propylenedioxythiophene hydroquinone 3,4-ethylenedioxythiophene), pEP(NQ)E = poly(3,4-ethylenedioxythiophene 3,4-propylenedioxythiophene naphthoquinone 3,4-ethylenedioxythiophene), P3HT:PCBM = poly(3hexylthiophene):[6,6]-phenyl C_{61} butyric acid methyl ester, PLA = poly(lactic acid), LED = light emitting diode.

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Table 2 Highlighted examples of studies of material and devices without in-depth environmental assessments

Function	Research concept	Key materials	Mechanical properties	Environmental assessment	Ref.
Device-level					
Circuits	A novel fabrication method and architecture for soft electronics	Toluene, Ag, Ni, Fe, C, GaIn, SIS, Fe_3O_4 & PVA	Stretchable	Demonstrating recycling and repairability	47
Biosensors	Upcycling of no longer used CDs	CD, tattoo paper, PI, PMMA, PCL, chitosan, SWCNT & Prussian Blue	Stretchable	Degradation in different solvents including PBS@37 °C	48
HBTs, Schottky diodes, MIM capacitors	High performance electronics on CNF substrates with a minimized use of toxic semiconductors	TEMPO-oxidised CNF, bisphenol A-based epoxy resin, GaAs, GaInP, Si, C, $Al_{0.96}Ga_{0.04}As$, PI, Pd, Ge, Au, PDMS, Cu & TiO_2	Flexible	Quantification of the amount of arsenic and water needed for the device, compared to consumer electronics & fungal biodegradation	49
Battery	Fungal mycelium substrates	Mycelium, Cu, Au, Zn, acetylene carbon black, xanthan powder, MnO_2, Cr, shellac, PEDOT:PSS, Ag, ammonium chloride and zinc chloride	Flexible	Aerobic disintegration in soil at 58 °C	50
LED, LEC, circuit bord, strain sensor	A biodegradable & photo-crosslinkable stretchable polymer	Poly(glycerol sebacate) acrylate, galinstan, PEDOT:PSS, Au, cellulose acetate, PDY-132, poly(caprolactone-*co*-trimethylene carbonate) & poly(caprolactone-*co*-trimethylene carbonate)	Stretchable	Biodegradability assessment according to ISO standards	51
Electronic component-level					
Large range of devices on biodegradable polymer substrates	Fabrication method that separates the processing of electronic systems & the biodegradable polymer	PLGA, Mg, SiO_2, Si, PDMS, rice paper, PLA & PCL	Flexible	Degradation in PBS@37 °C	53
Sensor	Highly deformable temperature sensor	Mg, Si_3N_4, SiO_2, Ecoflex, PMMA & NaCl	Stretchable	Dissolution tests in water–NaCl solution@25 °C & cytotoxicity tests	54
Sensors	Laser-based method to make biodegradable electronics	Mg, Si, PLA, Zn, PLGA, wax, BTP, cellulose acetate, Fe, Mo	Stretchable	Bioresorbability in PBS@95 °C for 10 days & *in vivo* biocompatibility for 8 weeks	55
Thin-film transistor	A crystalline nanocellulose dielectric ink that is compatible with CNT & graphene inks, allowing for all carbon TFTs	CNC, CNT, graphene, toluene, NaCl, AgNW, paper	Flexible	The inks were recycled 5 times and kept good performance	56
Cardiac jacket, actuator & conductive elastomer	Highly elastic biodegradable elastomer	PLCL, PEDOT:PSS, P14(TFSI), Mo, SiO_2, Mg & Si	Elastic	Fungal biodegradability & degradability in PBS@37 °C & cytotoxicity studies	57
Electrocardiogram (ECG) electrodes and pressure sensors	Stretchable, self-healing, and recyclable conductive polymer composites	PEDOT:PSS, PU, PEG	Stretchable	The conducting polymer composites were mechanically cut into small pieces, reheated at 100 °C to facilitate remoulding	59
Thin-film transistor	Biodegradable & stretchable polymeric semiconductor	P(DPP-PPD), E-PCL, Au, SEBS	Stretchable	Degradability in acidic solution (pH $\sim$ 0.5), *in vitro* cyto-toxicity studies	60
OFET	Combining the synthesis and processing of high performance organic semiconductors for OFETs in one-pot and in water	SDS, PIDTBT, PDPPTBT, Pd, methanol, toluene	Flexible	Synthesis in 1 : 10 water : toluene & dialysis instead of Soxhlet	61
Energy storage and power source component-level					
Super-capacitor	Fully printed and disposable EDLC	TEMPO-modified CNF, CNC, glycerol, shellac, graphite, carbon-black, activated carbon, NaCl	Flexible	ISO standard 20200 composting until 50% mass loss	64
Battery	Battery with dual electrolyte to get a high performance eco/bioresorbable battery	Mg, polyanhydride, iodine, super P, PLGA, ethyl acetate, chitosan, Mb, choline chloride & urea	Flexible	Dissolution in PBS@37 °C & 85 °C and biocompatibility studies *in vivo*	65
Battery	Biodegradable redox-diffusion battery	Alizarin red S, lignosulfonate, CNF, PEDOT:PSS, PU, nanographite & PGS	Stretchable	Biodegradability assessed by soaking in PBS at various temperatures	66
Battery	Biodegradable and stretchable battery with high energy and power density	PGS, MoO_3, xanthan gum, Mg, calcium alginate & $CaCl_3$	Stretchable	Battery	67
Battery	Edibility	Quercetin, riboflavin, nori algae, beeswax, $NaHSO_4$, Au, activated charcoal & ethyl cellulose	Rigid	Materials are below the limit of toxicity for human consumptions	68

SIS = styrene isoprene styrene, PVA = poly(vinyl alcohol), PI = poly(imide), PMMA = poly(methylmethacrylate), PCL = poly(caprolactone), SWCNT = single-walled carbon nanotube, TEMPO = tetramethylpiperidine-1-oxy, PDMS = poly(dimethylsiloxane), PDY-132 = polymer emitter super yellow, PLGA = poly(lactic-*co*-glycolic acid), BTP = bioresorbable thermoplastic polymer, CNC = cellulose nanocrystals, CNT = carbon nanotube, NW = nanowire, PLCL = poly(L-lactide-*co*-ε-caprolactone), P14(TFSI) = *N*-methyl-*N*-butylpyrrolidinium bis(trifluoromethanesulfonyl) imide, p(DPP-PPD) = poly(diketopyrrolopyrrole p-phenyldiamine), SDS = sodium n-dodecyl sulfate, PIDTBT = poly(indacenodithiophene-benzothiadiazole), PDPPTBT = poly(diketopyrrolopyrrole thiophene-benzothiadiazole), CNF = cellulose nanofibers, PGS = poly(glycerol sebacate), PU = polyurethane, PEG = polyethylene glycol.

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came at the cost of hazardous organic solvents and petroleum-based substrates, with no formal environmental assessment of their process. Brown *et al.* showed upcycled compact discs (CDs) into flexible devices using low-energy fabrication and waste valorisation, but without formal environmental assessment.[48] On the other hand, Jung *et al.* developed biodegradable cellulose nanofibril substrates for flexible GaAs-based electronics, mitigating plastic waste but relying on toxic, rare metals without quantifying their trade-offs.[49] Similarly, Danninger *et al.* proposed ''MycelioTronics'' using fungal mycelium skins, which biodegrade under composting conditions and enable disassembly, but scalability and full life-cycle impacts remain unassessed.[50]

More robust environmental assessment examples have been shown. For example, Held *et al.*, who demonstrated stretchable biodegradable electronics with poly(glycerol sebacate acrylate) elastomers and Galinstan liquid metal (Ga, In & Sn) interconnects.[51] Biodegradability of the elastomer substrate was rigorously validated following ISO 14855-1 and ISO 14851 standards, ensuring environmental disintegration under composting and aqueous conditions. The mechanical and electrical performance were maintained during use, although safe recovery strategies for Galinstan residues after substrate degradation remain an open challenge. Nair *et al.*'s ''Leaftronics'' minimised synthetic processing using natural wood-based lignocellulose leaf scaffolds and included a cradle-to-gate LCA, quantifying reductions in carbon footprint relative to non-bio-based alternatives. However, their lab-scale LCA was limited in scope and lacked prospective modelling.

More recently, Dulal *et al.*'s SWEET platform (Sustainable, Wearable, and Eco-Friendly Electronic Textiles) integrated biodegradable substrates, low-toxicity inks, and a comprehensive LCA across 17 impact categories, but they excluded use phase and end-of-life impacts.[52] Finally, Liu *et al.* introduced paper-based printed circuit boards (P-PCB) fabricated *via* additive manufacturing and biodegradable substrates reporting approximately two orders of magnitude lower environmental burdens across multiple categories compared to conventional epoxy-based PCBs. 9 different impact categories were considered. The use of renewable paper substrates and simplified additive fabrication processes were key drivers of the reduced impacts. In the study, they also identified the use of silver flakes as conductive fillers as significant contributors to human toxicity. This case exemplifies how targeted material and process redesigns, even at the component and interconnect level, can notably improve the environmental performance profile of the technology. However, prospective impacts and impacts of the use phase remain to be investigated.

3.2. Electronic component level

The electronic components of wearable devices include active layers such as semiconductors and conducting interconnects that influence the device's operational characteristics. These are often composed of persistent, non-recyclable, and non-biodegradable materials. Recent efforts to enhance the environmental performance of electronic components in wearable systems have primarily focused on biodegradability, recyclability, the use of bio-sourced materials and less toxic solvent either during material synthesis or device processing.

Hwang *et al.*[53] and Salvatore *et al.*[54] demonstrated early examples of biodegradable transistors and sensors using ZnO, Mg, and compostable substrates, achieving full degradation without sacrificing functional integrity. However, both studies lacked formal environmental assessments and relied on materials or fabrication techniques such as vacuum deposition or thick encapsulations that complicates scalability. Similarly, Yang *et al.* advanced the field with spatially programmable, bioresorbable devices using laser-structured electrodes based on biodegradable metals, such as magnesium and zinc, and elastomer substrates.[55] Their work is particularly relevant for transient biomedical implants that are conceptually designed for biodegradation and bioresorption inside the body, or for single use disposable devices that can degrade safely in the environment. The biodegradation test of all materials was demonstrated *in vivo* under accelerated conditions (phosphate buffered solution (PBS), 95 °C, 8 weeks), but broader environmental life-cycle impacts were not evaluated in detail.

More recent innovations have targeted environmental performance through scalable processing and eco-friendly material sourcing. Williams *et al.* introduced recyclable, printable carbon-based transistors using the biopolymer, cellulose as the active dielectric layer and substate material which enabled low-temperature recovery of both substrate and conductors.[56] However, long-term environmental degradation of residual carbon nanomaterials was not assessed. More recently, Han *et al.* presented a stretchable and biodegradable elastomer from bio-derived polymer used as a binder for a conductive electrode composite, active actuator component and substrate layer.[57] The elastomer exhibited mechanical stability (softness and stretchability) while maintaining electrical performance and exhibited complete biodegradation under simulated composting conditions within a few months.

Self-healing and reprocessable materials at the electronic component level are gaining attention for their ability to extend device lifetimes and reduce waste by enabling components to repair damage or be recycled.[58] For example, Kim *et al.* have recently reported a stretchable, self-healing and fully recyclable conductive polymer blend, which exhibited stable electromechanical performance even after being recycled 20 times.[59] They assumed that end-of-life devices made from the material could be collected and reprocessed under mild conditions (≈100 °C and low pressure) instead of landfilling, thereby saving raw materials and avoiding the impacts of producing new components.

Tran *et al.* introduced a new class of semiconducting materials that are both fully degradable and stretchable, aiming to meet the requirements of transient and bioresorbable electronics.[60] Their approach combined a conjugated donor–acceptor copolymer, designed with hydrolytically cleavable ester side chains, with a biodegradable elastomeric matrix to achieve mechanical compliance and controlled degradation.

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However, the degradation conditions were achieved under highly acidic (pH ∼ 0.5) conditions.

In another paper on semiconducting polymers, Rahmanudin *et al.* highlighted the need for making the synthesis purification and processing of the organic semiconductor into flexible organic transistors more environmentally friendly.[61] The work focused on reducing the number of fabrication steps from the synthesis and purification of the polymer, right up to the film processing of the semiconducting layer in a transistor. All in one-pot and mainly with water as a solvent media. The authors claimed to minimize the use of toxic and volatile organic solvents such as toluene, which is typically used in polymer synthesis, and avoided chlorinated solvents like chlorobenzene that is commonly used to dissolve the polymer during film processing, as used by Tran *et al.* However, lab-scale values were used as a basis of comparison between conventional synthesis, purification and processing methods with their synthesis-to-device in water approach. Scale-up synthesis and printing conditions were not considered, and rare metal palladium catalysts were needed for the polymerisation.

These examples illustrate that efforts at improving the environmental performance at the electronic component level spanning transistors, sensors, and active layers. Early work focused on achieving basic biodegradability in rigid devices, while more recent studies extend degradability and recyclability into fully stretchable, functional systems suitable for wearable and transient electronics. However, despite promising demonstrations of material breakdown and functional resilience, comprehensive LCAs remain rare, and future efforts should aim to systematically quantify the environmental benefits of component-level innovations across the full life cycle.

3.3. Energy storage and power source component level

The power source is the central enabler of any wearable electronic system, providing the energy required for long-term remote operation, real-time sensing, and wireless data transfer and processing. However, conventional batteries and energy storage systems are often rigid and bulky, posing serious sustainability challenges for next-generation wearable technologies.[14] Device-level power management strategies have been proposed to mitigate these challenges by combining ultra-low power electronics with battery-free device configurations, and instead integrate energy harvesting modules (such as photovoltaics, thermoelectric, or triboelectric generators) and wireless power transfer to reduce or eliminate dependence on conventional batteries.[13] Although such power strategies are advancing, current technologies typically provide only low, intermittent power outputs insufficient for complex or power-hungry wearable functions. Consequently, it can be argued that batteries remain the most practical solution for enabling long-term, autonomous operation of advanced wearable systems.[13,14,62]

To address the environmental performance of energy storage systems, a new class of biodegradable, edible, and recyclable ‘‘transient batteries’’ has emerged.[63] These innovations aim to align device lifetimes with application needs while minimizing environmental burdens at end-of-life. The following examples highlight recent advances towards higher environmental and resource performance in this area.

For example, Aeby *et al.* developed low-power supercapacitors using biodegradable cellulose substrates and aqueous inks, although their energy density and lifespan restrict broader applicability.[64] Similarly, Huang *et al.* introduced a magnesium–iodine battery with complete dissolution under physiological conditions, achieving coin-cell-level energy density.[65] Yet, neither study included formal environmental assessments, leaving their broader environmental trade-offs unquantified.

Biodegradable stretchable batteries are also advancing. Rahmanudin *et al.* designed a soft battery system with plant-based components and mild degradation pathways.[66] While the use of bio-sourced materials and their biodegradability may be justified, the low battery performance and quantification of embodied energy, sourcing impacts, or scalability was not conducted, leaving open questions about broader environmental trade-offs at larger scales. Similarly, Karami-Mosammam *et al.* used kirigami-structured magnesium and molybdenum electrodes on biodegradable substrates to achieve high mechanical durability and energy density, but again only material degradation under physiological conditions was tested.[67]

Ilic *et al.* took a novel approach by developing an entirely edible, rechargeable battery using food-grade components.[68] All battery components were proven to be non-toxic and digestible according to food safety standards, offering a safe pathway for disposal through biological metabolism. Environmental performance was considered using biodegradable, renewable, and food-safe materials, although no LCA was conducted. As with other transient technologies, scalability, mass production energy demands, and sourcing impacts remain to be fully considered for broader environmental evaluation.

In contrast, Zhang *et al.* provides a detailed environmental evaluation of flexible all-organic battery technologies through two complementary studies. In their first study, they performed a cradle-to-gate LCA of laboratory-scale all-organic batteries, identifying major environmental hotspots such as solvent use, catalyst consumption, and energy-intensive synthesis steps.[69] In a follow-up study, they extended their analysis to a prospective LCA, modelling the environmental impacts of industrial-scale production and comparing future all-organic batteries to conventional flexible lithium-ion batteries.[70]

Mittal *et al.* integrated their innovation with an environmental assessment within a single study.[71] They introduced a transient zinc-ion battery specifically designed from the bottom up for high environmental performance. Their battery combined a biodegradable polydopamine-derived organic cathode, a zinc metal anode, and a benign aqueous electrolyte, packaged within biodegradable substrates. The device achieved excellent electrochemical performance with an ultralong operational lifespan of over 10 000 cycles while retaining mechanical flexibility suitable for wearable applications. Additionally, they conducted a cradle-to-gate LCA to quantify the environmental

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impacts of raw material extraction, battery fabrication, and packaging in terms of 18 impact categories. The analysis revealed that the energy consumption, particularly from oven drying, represented the dominant contribution to most environmental categories. Although this could be a lab-scale artefact that would not be there during large-scale manufacturing, while the materials themselves contributed minimally due to their benign and abundant nature. The study highlighted clear improvement strategies for future pilot-scale manufacturing, notably through energy optimization and material substitution.

Expanding beyond batteries, other studies have assessed the sustainability of alternative power sources. Välimäki *et al.* studied how replacing poly(ethylene terephthalate) (PET) made from virgin raw material with recycled PET (rPET) and bio-based polymers as well as metals and metal oxides with poly(3,4-ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) affected the environmental footprint of organic photovoltaics (OPVs).[72] The authors also examined the scalability in the manufacturing of these devices by using printing techniques. Both cumulative energy demand and greenhouse-gas emissions were assessed in a life cycle perspective for six different devices and the authors were able to compare the different footprints of both the polymer substrates and the metals with PEDOT:PSS. Still, there are other potentially interesting impact categories, and no attempt to model future impacts of the technology were performed.

Similarly, Ahmed *et al.* conducted an LCA on two different triboelectric nanogenerators (TENGs) where one was based on an earlier study.[73] In addition, the authors also included a techno-economic analysis. In this study, the authors highlighted the environmental hot spots of the TENGs and show the competitiveness of the technology compared to photovoltaics when it comes to energy payback time (EPBT). 11 different impact categories were considered, and a thorough sensitivity analysis covering different design parameters was performed. Even if the two TENGs had different operation modes and efficiencies, the use phase as well as the EoL was excluded from the assessment, and no prospective assessment was performed.

Across the examples surveyed, most studies focused primarily on achieving material-level environmental performance measures, such as biodegradability, bio-sourced or biocompatible materials (Aeby *et al.*, Huang *et al.*, Danninger *et al.*, Rahmanudin *et al.*, Ilic *et al.*). Environmental performances were typically demonstrated through simplified material degradation tests or qualitative descriptions of benign components, but systematic quantification of life cycle impacts remained rare. Mittal *et al.* and Zhang *et al.* stand out for incorporating cradle-to-gate LCAs of their systems.

4. Recommendations for early-stage environmental assessment of wearable electronics

Section 2 discussed the importance of applying a life-cycle perspective, selecting appropriate functional units, including multiple impact categories, and adopting a prospective perspective to assess future environmental performances. Section 3 demonstrated that so far, environmental assessments in the area of wearable electronics are often limited to considering single parameters, such as (bio)degradability or the use of biomaterials to justify environmental performance. Here, we provide four recommendations on how to advance and further integrate environmental assessment practice within the field (Fig. 3).

4.1. Environmental performance ≠ (bio)degradation

There is a strong focus on (bio)degradability in the studies reviewed in Section 3, to the extent that some come close to equating degradability with high environmental performance. However, from a life-cycle perspective, this is not necessarily the case. Degradability might be beneficial given the EoL scenario that the wearable device is landfilled or simply tossed into nature. But from a circular economy perspective, that should not be the encouraged EoL scenario for advanced, high-value materials. Rather, their value should preferably be maintained through different so-called R strategies, such as reuse, repair, refurbish, and recycle.[74]

Degradability might even be a problem if recycling practices are in place and there is degradation of materials during recycling processes, referred to as "downcycling".[75] Exceptions where degradability might be beneficial also in a life-cycle perspective include applications where recycling and other R strategies are particularly challenging, like for electronic implants inside the human body. In such cases, degradation in the body (or subsequently in the environment) might be a preferable EoL option. However, we dissuade from considering degradability a proxy for environmental performance in general. Instead, we recommend performing LCA studies where different EoL options are considered, thereby revealing the most environmentally preferable option(s). In that context, results from degradability studies can be used as input data for, *e.g.*, landfill options. Degradability results can thus be part of a more holistic environmental assessment, rather than stand-alone proxies for environmental performance.

In addition, we note that several of the reviewed studies consider biodegradation to limited extents (see Table 2). Sometimes, the conditions applied are far from those present in the human body or the environment, *e.g.*, with higher/lower pH or temperature. Also, sometimes only part of the device was subject to biodegradability tests, or the test was run over a too short amount of time only proving partial degradation but claiming that the whole device is biodegradable. Such constraints limit the environmental relevance of biodegradability tests and makes the measured result an even less of a valid proxy for environmental performance. We therefore recommend that degradability tests are performed for the entire device and under relevant conditions for the envisioned EoL scenario.

4.2. Limitations of lab-scale LCA

We also noted that the majority of the LCA studies performed are so-called lab-scale LCAs, meaning LCAs of lab-scale

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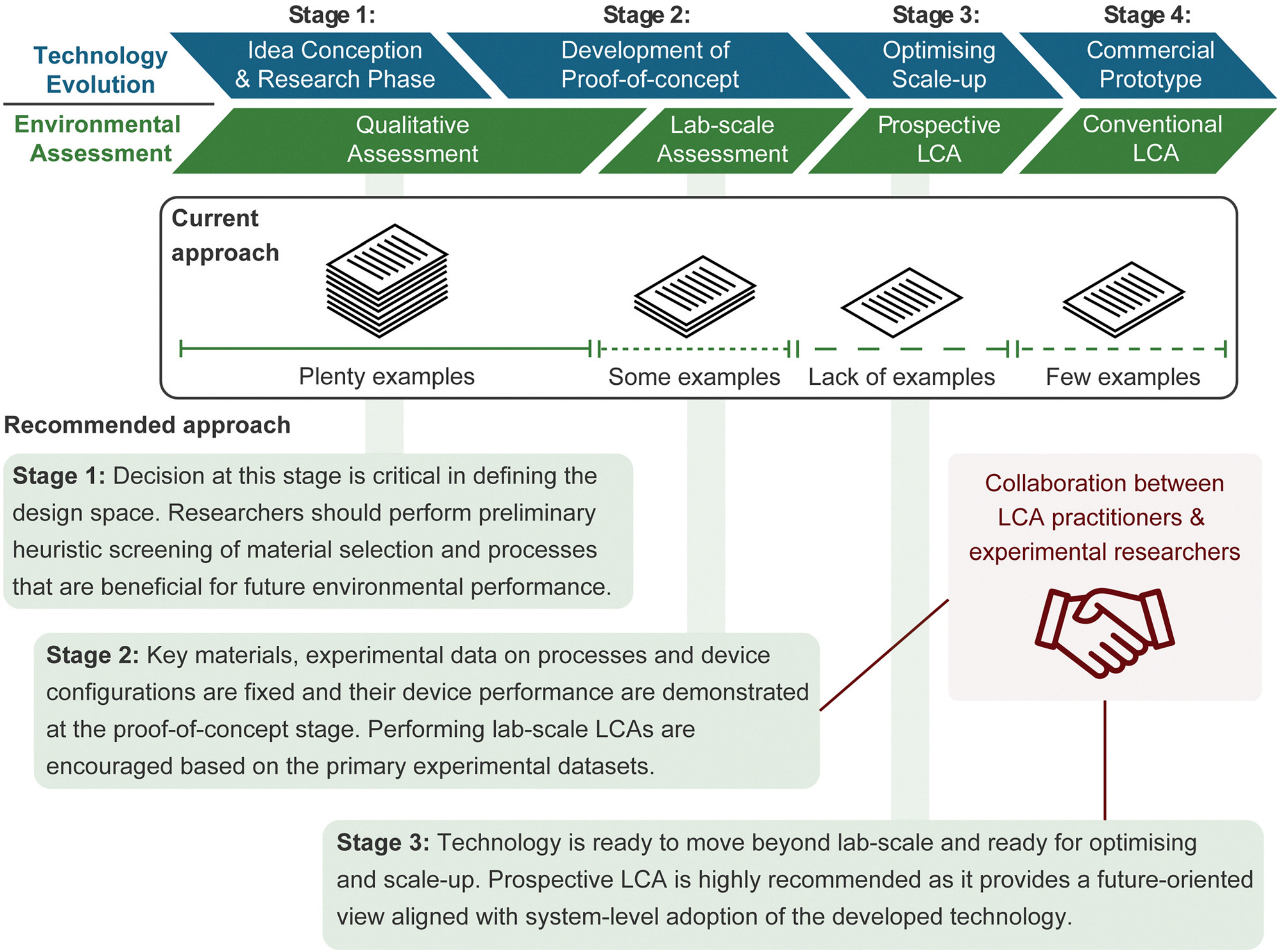

Stage 1: Decision at this stage is critical in defining the design space. Researchers should perform preliminary heuristic screening of material selection and processes that are beneficial for future environmental performance.

Stage 2: Key materials, experimental data on processes and device configurations are fixed and their device performance are demonstrated at the proof-of-concept stage. Performing lab-scale LCAs are encouraged based on the primary experimental datasets.

Stage 3: Technology is ready to move beyond lab-scale and ready for optimising and scale-up. Prospective LCA is highly recommended as it provides a future-oriented view aligned with system-level adoption of the developed technology.

Fig. 3 Illustration of the different stages of the technology evolution process at pre-commercialisation and our recommended approach of when and how to integrate environmental assessment.

technology.[80] This represents a more holistic attempt at environmental assessment compared to qualitative assessment of merely considering, *e.g.*, biodegradability or the use of bio-derived materials. Regarding the important aspects described in Section 2, this approach considers a life-cycle perspective, often also with multiple impact categories. Specifically, established "packages" of impact assessment methods are often applied, such as in Dulal *et al.*[52] and Mittal *et al.*[71]

As evident from several of the reviewed studies, lab-scale LCAs can yield relevant information about environmental performance, not least to experimental researchers engaged in the early-stages of the research process. However, lab-scale LCAs lack a prospective perspective, which introduces some limitations. When technologies mature and production processes are scaled up to match increasing demand, production processes and other activities in the life cycle typically change. For example, magnetic stirrers and manual transfer of liquids are typically replaced by in-tank stirring and pumping at larger scale.[81] This means that some hotspots identified at lab scale might change in the future, regardless of whether they are highlighted in a lab-scale LCA or not. For example, extensive use of solvents or placing individual substrates in massive ovens will likely be subject to solvent recirculation and more efficient, continuous ovens, if ever scaled up. In addition, comparing lab-scale to large-scale technologies can often be of questionable relevance, since the lab-scale technology has not had time to develop yet.[44] Lab-scale technologies are therefore questionable to assess in LCAs with the aim to make comparative assertions to anything but other lab-scale technologies. Therefore, pointing out such hotspots at the lab scale can be of limited value. By performing upscaling already in the LCA study, likely hotspots at large-scale production can instead be identified. Naturally, such upscaling comes with uncertainties, but it can nevertheless potentially provide more relevant results. The functional units used in the lab-scale LCAs are mainly a certain area of the wearable electronic device (*e.g.*, 1 m^2) (see Table 1). For power sources, 1 kWh storage capacity is often used, which is also common in LCAs of non-flexible batteries.[82] However, the surface area of a device tells little about its technical performance and does not allow for comparisons to other technologies with different per-area performance. Turning to functional units that more reflect the function of wearable devices might be advisable, particularly for comparative LCAs.

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Such functional units that consider the performance and specific properties of materials can allow more meaningful ("apples-to-apples") comparisons in LCAs, especially for new materials.[83] Below, we explore several alternative functional units that were applied at early stages of development.

For energy storage devices, a functional unit of 1 kWh stored, or 1 kWh energy throughput is conventional in LCAs of traction and stationery batteries and might be useful for wearable energy storage devices as well.[84] For example, a novel organic battery with low specific energy (Wh kg^{-1}) will need more material per unit of energy stored and will then show higher impacts per kWh.[70]

Similarly, flexible and stretchable conductors used as interconnects in PCBs often use critical raw materials with metals such as Ag, Au, and Ga, or specialized nanomaterials (CNTs, graphene, *etc.*). Replacing or reducing certain metals (like using less silver or avoiding scarce indium) is a common strategy to reduce the environmental impact.[25] Incorporating material usage efficiency by metrics like specific conductivity (Siemens per meter over gram per cubic centimetre, S m^{-1} g^{-1} cm^3) considers volumetric density and mass of conductor used.[85] A strictly mass-based comparison (impact per kg) would favour carbon or copper over silver since silver's production footprint is much higher. However, silver has a higher conductivity, meaning much less is needed to achieve a given electrical performance. This is where performance-based metrics are essential. Nassajfar *et al.* introduced a "double-parameter comparison" for printed conductive inks that simultaneously evaluates their environmental impact and electrical conductivity.[86] They showed that while replacing silver flakes with copper or graphite significantly reduces impact, the lower conductivity of those alternatives must be accounted for in functional terms.

Sensors in wearables can similarly benefit from more performance- and property-related functional units. Rather than impacts per sensor or per cm^2 of sensor area, one can define the unit in terms of sensing performance, such as "per detection event", "per unit of sensitivity achieved", or "per measure of signal quality over a device's life". A recent LCA of printed sensors used the functional unit for monitoring a target gas at a given detection limit for one day.[87] This kind of functional unit captures environmental impacts per achieved sensing function.

By using performance- and property-based units, researchers can identify which materials or components contribute the most to environmental burdens per unit of function. This can encourage both environmental impact reduction and improvements in technology performance as the technology develops.

4.3. Call for prospective LCA

Considering the limitation of lab-scale LCA discussed in Section 4.2, as an even further step, we recommend researchers and developers of wearable electronics to also consider a prospective perspective. This means going beyond lab-scale LCA and towards prospective LCA, where the technology is modelled at a future point in time.[42] Among the reviewed studies, only one prospective LCA study was identified, namely that of Zhang *et al.*,[70] which was a prospective follow-up study of a previous lab-scale LCA of the same technology.[69] Performing such sequential studies with an initial lab-scale LCA followed up with a prospective LCA can generally be valuable. The lab-scale LCA provides an overview of the emerging production system and initial hotspots, which can then be addressed in the prospective LCA. Such a sequential approach has previously been applied in, for example, LCA studies of metal recovery from e-waste[80] and wood products.[88]

That said, we acknowledge that prospective LCA constitutes an advanced environmental assessment approach, which might sometimes be difficult to apply at the very early stages of the research process and requires certain competences. Furthermore, approaches to change some background system processes over time across the whole life cycle exist (such as electricity and cement production), but these approaches require specific LCA software, and do not yet contain all potential inputs to life cycles (*e.g.*, not yet chemicals).[45] While there exists guidance on how to scale up chemical processes,[81] other aspects of emerging technologies can be more challenging to scale up.

Early-stage innovations might show great performance in the lab, but their scalability, sustainability and long-term durability in real-world conditions are unproven. They generally lack a mature manufacturing infrastructure and supply chain, meaning there are few existing facilities, suppliers, or trained workers ready to produce them at scale.[89] Economically, new technologies do not yet benefit from economies of scale, so unit costs remain high and critical materials or components may be scarce or hard to source, creating supply-chain constraints. Indeed, moving from controlled laboratory prototypes to practical, large-scale deployment is often the hardest step (the infamous "valley of death" where many fail).[90] There may also be existing regulatory hurdles, where novel products can fall outside, requiring new testing protocols and approvals before they can enter the market.

In the next section, we provide further recommendations about the timing and integration of different environmental assessment approaches into innovation of wearable electronics.

4.4. Timing and integration of the environmental assessment

To address the design paradox for environmental performance of wearable electronics (Fig. 2), environmental assessments can inform different stages of the early-stage research process. Here, we refer to three critical pre-commercialisation stages of the process (Fig. 3), which constitute an aggregation of the more detailed technology readiness levels measurement system.[91]

- Stage 1: idea conception & research phase.
- Stage 2: development of proof-of-concept at the lab scale.
- Stage 3: optimizing and scale up.

To this list, a subsequent step 4 involving commercialization can be added (Fig. 3), at which the product can be subjected to more standardized assessments of environmental performance, such as conventional LCA standardized in environmental product declaration guidelines.[92] Some examples of

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wearable electronics that have already been subject to such assessments were identified in the review.[93,94] However, the present perspective mainly concerns the pre-commercialisation steps 1–3 related to the research and innovation process.

4.4.1. Stage 1: idea conception & research phase.

At stage 1, the earliest materials or wearable device research phase, detailed environmental assessments are generally challenging due to a lack of data and even knowledge about what the eventual technology or product will look like.[95] Also, such early idea conceptions generally take place in teams of experimental researchers only, without detailed knowledge about LCA and other environmental assessment tools. However, this stage is still critical for defining the future design space of wearable devices. The goal is to flag potential issues early and select materials and processes that are likely to lead to beneficial environmental performance in the future. For example, the following heuristics can be considered:

- Applying the principles of green chemistry during the conception of the idea and the research phase.[96,97]
- Selecting starting materials from renewable and abundant sources, as opposed to fossil or other scarce sources. There are several comprehensive review articles that discuss the use and properties of sustainable materials in wearable devices ranging from electronic[16,24,98,99] and energy[14,63] components, large-area manufacturing[13,100] to packaging/encapsulation layers.[46,101,102]
- Identifying the hazard classification of materials, such as avoiding REACH[27] or Classification, Labelling and Packaging (CLP)-listed substances,[103] and using chemical databases such as Chemsec's Substitute It Now (SIN) list.[104]
- Presumed environmentally benign process settings, such as solvent-free or the use of low-toxicity solvents (*e.g.*, aqueous media, biocompatible liquids), mild processing conditions (*e.g.*, low temperature (<100 °C), vacuum-free and ambient environments).
- EoL considerations should depend on the design concept and tuned accordingly, such as recyclability, composability, persistent materials, or bioresorbable systems. Biodegradation can be part of such heuristic evaluations, but as discussed in Section 4.1 should not be seen as the sole proxy for environmental performance.

4.4.2. Stage 2: development of proof-of-concept at the lab scale.

At Stage 2, key materials and device architectures are typically fixed, and the proof-of-concept is demonstrated at the lab scale, and enough information is typically available to perform early LCAs. A lab-scale LCA can be a first step, or prospective LCA (see Table 1 for reported examples) that also involves upscaling of the technology. Primary experimental data from syntheses, fabrication, or EoL treatments at the lab scale can be utilized. We recommend such studies to be performed in close collaboration between experimental researchers and LCA practitioners. The LCA practitioner can then take on different roles in the collaboration, such as guide research and development towards better environmental performance, direct future research and development activities, or (more pragmatically) ensure that environmental requirements towards the funder are fulfilled.[105]

4.4.3. Stage 3: optimising and scale-up.

At stage 3, the technology is deemed fit to leave the early lab bench and move towards commercialization. This can manifest as larger-scale tests in labs under more optimized conditions and pilot plant trials. At this stage, there is typically enough information about the wearable technology to initiate both lab-scale and prospective LCA. The prospective LCA can provide insight into the future environmental performance of wearable electronics under different scenarios given system-wide adoption, helping in anticipating trade-offs before they become locked into large-scale deployment. Prospective LCA of emerging wearable electronics technologies might include:

- Process upscaling using stoichiometric modelling, equipment scaling, and/or proxy industrial data.
- Energy grid projections using tools like the above-mentioned premise to model future electricity mixes.
- Modelling of the use phase, including integration with energy recovery or power management.
- Scenario modelling of different EoL routes, such as reuse, recycling, biodegradation, incineration, and landfilling.

4.5. Challenges in implementing environmental assessments and opportunities for closer collaboration

Implementing LCA in early-stage lab settings is non-trivial, with barriers such as lack of LCA know-how, data gaps, and resource limitations. It further justifies our recommendations for tailored environmental assessment strategies that are feasible for researchers at different development stages, as well as collaborations with LCA experts. The main challenges are:

- Limited LCA expertise: many experimental research groups do not have in-house training or experience in performing LCAs, especially not prospective LCA. We recommend that experimentalist collaborate with environmental scientists and LCA practitioners to effectively carry out such analyses, primarily at Stage 2 (Fig. 3). Not only will it help bridge this expertise gap and ensure the assessment is done rigorously, but it will also foster closer interactions between the two disciplines.
- Data availability: as discussed earlier, obtaining reliable life cycle inventory data for novel materials or lab-scale processes under development is difficult at early research stages. Researchers may need to generate primary data or use proxy data for new materials, which adds uncertainty, especially in prospective LCA. Experimentalists may also face resource limitation in accessing inventory data. This emphasizes why data limitations can hinder comprehensive environmental assessments at the early stages (Stage 1 and 2) of the development (Fig. 3).
- Resource and time constraints: performing (especially prospective) LCA requires considerable time, effort, and sometimes specialized software or database access. While it is reasonable that early-stage research projects developing sustainable technologies prioritize funding for material or process development, some allocation of resources to performing LCA is also advisable.

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5. Conclusions

This perspective provides important aspects to consider when assessing the environmental performance of wearable electronic devices, and reviews to what extent these are applied in practice. Based on this, some recommendations are provided (Fig. 3). First, (bio)degradation is commonly considered in studies involving innovation of wearable electronics but should not be used as a sole proxy for environmental performance. Second, lab-scale LCA is becoming relatively common to assess the environmental performance and constitutes a more holistic approach, although it might identify irrelevant hotspots present only at the lab scale. Third, prospective LCA is an underused approach that could potentially bring important insights into the future environmental performance of wearable electronics. Forth, timing of the environmental assessment is important. During idea conception, lack of knowledge and data probably often prevents anything else than assessments using heuristics, such as not including toxic or scarce materials. During proof of concept, there is probably enough knowledge and data to start performing LCAs in close collaboration between experimentalists and LCA practitioners. During upscaling and optimization, prospective LCA is recommended to outline future impacts at large scale adoption of the wearable electronic device.

Together, these recommendations underline the need for an approach that enables researchers and developers to embed environmental assessment into the innovation pipeline from the outset. Overcoming the design paradox requires new approaches to sync environmental assessment and wearable material innovation. The recommendations are broadly aligned with more general calls for early consideration of environmental performance during the research process, such as the EU's safe and sustainable by design framework for chemicals and materials,[106] the EU Green Electronics working group that discusses the best practices of defining and achieving green electronics in hybrid printed electronics,[107] and Sweden's Wallenberg Initiative on Materials Science for Sustainability (WISE).[108] Our recommendations focus on wearable electronics by providing clearer guidance regarding which environmental assessment method to apply, and when during the research process they are feasible and most relevant.

Author contributions

A. R. and R. A. jointly conceptualized the Perspective. A. R., R. A., M. B. and F. W. drafted Section 1. A. R. and F. W. drafted Section 3. A. R., F. W. and M. M. contributed to the case study literature review and the bibliometric analysis. R. A. drafted Section 2 and contributed to the critical framing of LCA methodology. A. R. and R. A. drafted Section 4. K. T. provided feedback on the manuscript. All authors discussed the content, contributed to manuscript revisions, and approved the final version.

Conflicts of interest

There are no conflicts to declare.

Data availability

No new datasets, software or code were generated or analysed in the preparation of this Perspective. All information presented is based on published literature, which is cited throughout the manuscript. As this article does not report original experimental results or computational models, a data repository is not applicable. For transparency, the sources of all referenced materials are available in the reference list.

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