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Toward sustainable strips: a review of materials and environmental considerations for future health monitoring

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With an average of three tests per day, an estimated 591 billion glucose test strips are used globally each year. The rising prevalence of chronic diseases and the growth of self-measurement, quantified self, and biohacking movements are driving increased demand for electrochemical strips, underscoring the need for sustainable manufacturing and disposal strategies. This paper focuses on the working electrode while also addressing the reference electrode, strip production, and recyclability considerations. Novel working electrode materials, including carbon nanomaterials, MXenes, and green-synthesized metal nanoparticles, show promise for enhancing sensor sensitivity and selectivity while potentially lowering resource demand. However, their sustainability profile remains uncertain, as the energy- and chemical-intensive synthesis of nanomaterials may offset the benefits. Life cycle assessment (LCA) frameworks and the concept of a nanocircular economy are discussed as tools for evaluating and guiding sustainable design. At the same time, artificial intelligence opens new possibilities for sustainability by enabling the analysis of vast datasets to uncover hidden correlations between synthesis parameters and nanomaterial properties. These insights can guide more sustainable synthesis routes and support the design of novel nanomaterials and nanocomposites with tailored functionalities. By integrating material innovation with environmental considerations, the future of health monitoring strips can move toward minimizing waste, reducing dependency on critical resources, and aligning with global sustainability goals.

Sustainability spotlight

Disposable sensors, such as those for glucose self-monitoring, have become essential for managing diabetes; however, they produce significant waste, including large amounts of non-recycled plastic and metal. While nanomaterials promise improved sensor performance, sustainability claims often ignore the environmental costs of nanoparticle production and the uncertainties associated with scaling up to industrial levels. Sustainable manufacturing of disposable sensors emphasizes the use of biodegradable substrates, green solvents, and natural binders, aiming to replace hazardous materials while maintaining printability and performance. Supporting the UN SDG 3, UN SDG 9, UN SDG 12, and UN SDG 13 for sustainable health solutions and industrialization, this paper promotes the green production of testing strips and an outlook on more sustainable engineering practices.

1. Introduction

Economic development and aging populations are driving a rise in chronic diseases. To address this challenge, patients with non-infectious chronic diseases need effective clinical management strategies that emphasise self-management of their medical treatment and the mitigation of complications or disease progression.[1] Diabetes is a prime example: according to the International Diabetes Federation (IDF), approximately 540 million adults (20–79 years) were living with diabetes in 2024. By 2045, IDF projects that the number will increase to 783 million.

The history of self-monitoring for diabetes dates back to 1965, when Ames introduced the first glucose test strip using glucose oxidase. This strip was initially intended only for professional use.[2] By 1971, self-measurement glucose test strips became available,[3] with products like Chemstrip bG® by Boehringer Mannheim and Dextrostix® by Ames entering the market.[4] During the 1980s, the price of self-monitoring blood glucose meters dropped significantly, and it became a standard in treating patients with type 1 diabetes.[2]

People with diabetes often are required to test their blood glucose levels multiple times a day, depending on their treatment regimen, health condition, and healthcare provider's

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recommendations. Assuming an average of three tests per day, this translates to an estimated 591 billion test strips used globally each year. The global blood glucose test strips market size is projected to be worth USD 12 billion in 2025. It is forecast to reach USD 16 billion by 2030.[5] While testing requires resources and has its own carbon footprint, effective management of diabetes complications contributes to a more carbon-efficient planet by helping prevent serious complications that require resource-intensive treatments, hospitalizations, surgeries, and long-term care.[6]

The large-scale usage of these sensors results in millions of pounds of plastic waste annually, which is not currently recycled. According to a published paper on Turkey, 85.1% of patients disposed of their used blood glucose test strips in the general household waste.[7] While total waste is generated from various sources, such as test strips, glucose sensors, needles, insulin cartridges, and pens, needles and test strips account for the largest share by quantity.[8] Test strips are small, single-use analytical substrates used for point-of-care monitoring and are the focus of this paper. On the test strip, the working electrode is the key sensing component that produces the electrical signal in response to the analyte. Developing novel working electrode materials offers opportunities to enhance the sensitivity, selectivity, and stability of electrochemical biosensors across a wide range of analytes. However, the environmental impact of the processes used to produce alternative materials is rarely considered. Hosseinian *et al.* (2025)[9] highlight that silver contributes nearly as much to the carbon footprint as the main body of the strips, although it accounts for only 1% of the strips' weight.

Self-monitoring is becoming increasingly popular, and quantified self and biohacking are already significant movements. Scientists are advancing electrochemical sensors for diverse target molecules, facilitating comprehensive health monitoring. As these novel application areas mature, demand for electrochemical strips is projected to surge. Integrating sustainability into the development of electrochemical sensors for self-measurement, biohacking, and health monitoring is crucial to ensure that the growing market does not inadvertently worsen environmental challenges. Significantly, advancing measurement technologies can improve disease management, reduce complications, minimize treatments, and decrease hospital visits, all of which contribute to a more carbon-efficient planet.

In this paper, we discuss the environmental impact of test strips, review the environmental challenges and opportunities, explore alternative nanomaterials as electrochemical (bio) sensing transducers, and evaluate them from an environmental perspective. We conclude with a future outlook of new possibilities for finding sustainable materials.

2. Environmental impact assessment of typical glucose strips

Recent research performed by Hosseinian *et al.* (2025)[9] on self-monitoring blood glucose (SMBG) devices reveals that test strips significantly contribute to the environmental impact of these devices, due to their high usage and disposal requirements. These test strips, alone, account for approximately 20–23% of the total carbon footprint of SMBG devices. When combined with the plastic containers of the test strips and their associated packaging, their share of the device's total climate impact rises to 33–48%. This underscores the critical role of the materials in test strips and the design's impact on the environmental performance of glucose monitoring technologies. Beyond carbon footprint, a broader environmental impact assessment across multiple impact categories further emphasizes the need for material-conscious design.

The most effective strategy is usually simply using less material and improving the packaging-to-product ratio. The most typical packaging is made of plastic or paper materials due to their low cost and flexibility. Replacing plastic packaging with paper packaging can significantly reduce the environmental impacts.[10] In addition, the sources of plastics are 99% fossil-based, comparable to the global aviation sector's oil consumption, while only 1% is bio-based.[11] In response to environmental challenges posed by plastic use, bio-based plastics can help reduce package-related environmental burdens. Only a few bio-obased materials from renewable sources are biodegradable.[12] An LCA review compared the environmental impact of conventional plastics and biobased plastics. The results indicate that biobased plastics generally showed advantages in climate impact, but were heavily influenced by agricultural inputs, highlighting the need for optimized production processes.[10,13] In addition, using recycled content usually has a substantially lower carbon footprint than virgin materials. However, for medical devices, using recycled materials becomes more nuanced because regulatory, hygiene, sterility, and traceability requirements often constrain material choices.

The strips, although small and lightweight, contain materials such as polyester or polycarbonate, and their electrodes often include precious metals, including silver or gold. For printed sensors, the reference electrode, typically made of silver, accounts for 80–97%, the working and counter electrodes, made of carbon nanomaterials, 1–20%, and the substrate, 1–5% of the global warming potential (GWP).[14] However, the results from Hosseinian *et al.* (2025)[9] show that, as for the components found in the glucose sensors, while plastics dominate GWP, other materials contribute significantly in different ways. The production of polyester, for instance, is a major contributor to ozone depletion. At the same time, silver, despite comprising only a small fraction of the test strip mass, has a disproportionately high impact in several categories.[15] Silver has a significant environmental impact primarily due to the intensive processes required for extraction and refinement. These processes involve high energy use, chemical treatments, and the generation of hazardous waste. Even in small amounts, silver contributes heavily to freshwater and marine ecotoxicity by contaminating water sources and harming aquatic life. Additionally, silver is considered a scarce mineral resource, and its use in disposable products, such as test strips, raises sustainability concerns regarding long-term availability and responsible sourcing.[16,17] Regarding extracting precious raw

materials, gold mining also has severe environmental impacts, primarily due to pollution from tailings storage facilities. Storage of mining tailings may produce acid mine drainage and toxic metal contamination that can contaminate soil for decades.[18–20] Additionally, Norgate and Haque's (2012) results of LCA reveal that gold production has a disproportionately high environmental footprint, including high energy use (>0.1 million MJ per kg metal), water consumption (>0.1 million m^3 per tonne metal), and solid waste generation (>1 million tonne per tonne metal), which are mainly due to low ore grades and energy-intensive processes.[21] The greenhouse gas emissions of gold production were found to be lower than those of other metals when the global energy consumption was taken into account. Therefore, it is crucial to identify the most energy- and greenhouse gas-intensive stage, such as mining and mineral processing, to reduce the energy and greenhouse gas footprint.

Table 1 compares the life-cycle GWP of printed sensor components, while Fig. 1 shows the GWP of four representative WE materials produced by conventional techniques and green techniques. Fig. 1 was reproduced from Tables S3 and S4, which present the GWP of working electrode materials synthesized at the laboratory scale using conventional techniques and green methods, including those that utilize recycled feedstocks or renewable energy inputs. These findings suggest that evaluating environmental performance solely through carbon metrics may overlook crucial areas of concern. Additionally, laboratory-scale and hypothetical scaling-up scenarios used in LCAs can under- or overestimate the actual environmental impacts. The results of LCA studies depend on many factors, such as the functional unit, system boundaries, and impact categories. Especially, lab-scale LCAs are often scaled up to estimate LCA at an industrial scale with various methodologies, resulting in case-specific observations. Note that this review only addresses GWP at lab-scale LCA studies. Further improvements in carefully conducted industrial-scale LCAs, selecting alternative materials, and rethinking the life-cycle of test strips could lead to substantial environmental improvements in personal healthcare technologies.

3. Environmental opportunities and challenges of strip materials and manufacturing

A favourable opportunity is that (bio)sensors, in general, have demonstrated their potential to meet the principles of green chemistry and sustainability. By minimizing the use of samples, reagents, materials, and resources, and requiring less effort to produce results, these sensors align well with modern environmental demands.[25] The sustainability of the strips can be further evaluated through the framework of the "Nine Rs": Refuse, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, and Recover. The "Nine Rs" offer a holistic framework for ecological responsibility, collectively aiming to minimize waste, reduce environmental impact, and promote the sustainable use of resources throughout a product's life-cycle. The strips have certain limitations in this framework. *Refusing* disposable test strips is not a realistic option due to their medical necessity. However, this principle challenges us to explore alternatives, such as non-invasive continuous glucose monitors, which could reduce dependency on disposables over time. *Reducing* material usage in test strips can be achieved through design innovations. Additionally, optimizing strip manufacturing to lower waste and energy input supports this goal. *Reusing* test strips is not feasible due to hygiene and accuracy requirements. *Repair and refurbish* are more relevant to glucose meters than to strips. *Remanufacturing* strips is challenging due to contamination risks. *Repurposing* could include using expired or defective strips for educational, calibration, or research purposes, preventing immediate disposal. *Recycling* test strips remains difficult due to their mixed material composition (plastics, metals, reagents). Advances in material separation technologies or the development of mono-material strips could enable partial recyclability.

These challenges with strips reflect broader barriers in health technologies. Patient safety and ethical priorities often limit the use of recycled or alternative materials, while strict regulatory frameworks can slow the adoption of more sustainable solutions. The sector also struggles with a mismatch between rapid innovation cycles and extended product life-cycles, leading to outdated devices that are difficult to upgrade or repurpose. Additionally, effective waste management remains a significant hurdle, especially for single-use or bio-contaminated components that require special handling and are rarely recycled.

These challenges highlight the need to rethink material choices more broadly. In particular, as many emerging alternatives rely on nanomaterials, the concept of a *nanocircular economy* offers a valuable framework. It extends circular economy principles to nanoscale technologies, emphasizing design for recyclability, reduced toxicity, and resource efficiency throughout the material lifecycle.[26] This approach aims to mitigate environmental impacts, promote sustainable resource use, and enhance the safety and efficiency of nanotechnology by incorporating eco-friendly practices at every stage. It also emphasizes designing nanomaterials for recyclability, reducing toxicity, and ensuring they contribute to broader sustainability goals. An important consideration within the nanocircular economy is nanotoxicity. The environmental and biological risks of nanomaterials depend on factors such as size, shape, and reactivity, and can arise through direct effects on organisms or interactions with pollutants and ecosystems. While this review does not cover nanotoxicity in depth, comprehensive discussions are available elsewhere.[27–29] Adopting a nanocircular economy, in which nanomaterials are designed for reuse, recycling, and safe recovery, becomes essential to reduce environmental exposure and promote sustainable technological development.

3.1 Strip components

Electrochemical glucose strips are based on a three-electrode structure: a working electrode, a counter electrode, and a reference electrode. A potentiostat converts the detection of a target

Table 1 Life-cycle GWP of printed sensor components made from common materials used in glucose sensors[a]

Type of the sensors	Component	Materials	Impact categories	System boundaries	Functional unit (FU)	kg CO_2 eq.	kg CO_2eq. per FU	Ref.
Solar cell	Electron contact	Ag paste	Climate change impacts and cumulative energy demand (demand for fossil energy and total energy demand)	Partial LCA	1 m^2 of solar cell	Not available	~5	22
	Substrate (plastic components)	PET					~0.3	
		PLA					~0.3	
Gas sensor	Electrode materials	Ag	GHG emissions associated with the electrical energy demand for fabricating the sensor tag	Partial LCA	One sensor tag capable of wireless gas monitoring for 1 day	400	1×10^{-2}	23
		Cu				14	3×10^{-4}	
	Substrate (plastic components)	PLA				1.06	4.7×10^{-4}	
		PET				2.2	1.09×10^{-3}	
	Sensing material	ZnO				66	6.1×10^{-3}	
Voltammetric sensor	Substrate (plastic components)	HDPE plastic	Terrestrial ecotoxicity, terrestrial acidification, photochemical ozone formation, human health, photochemical ozone formation, ecosystems, metal depletion, marine ecotoxicity, land use, ionizing radiation, human toxicity, non-cancer, human toxicity, cancer, freshwater ecotoxicity, freshwater consumption, fossil depletion, fine particulate matter formation, climate change, including biogenic carbon, climate change, excluding biogenic carbon	Partial LCA focusing on the production process of each studied material	1 kg of the material	Not available	~3	14
	Reference electrode	Silver					~200–300	
	Working electrode and counter electrode	Carbon black					~3–5	
		CNTs					~50–70	
Printed circuit board	Substrate and conductive ink	PET–Ag	Abiotic depletion potential (elements), acidification potential, GWP	Cradle-to-grave	1 m^2 of a single-layer PCB. The net area of the inks is assumed to be 50% of the 1 m^2 area	Not available	10.9	24
		PET–copper					2.29	
		PET–graphite					0.56	
		PLA-Ag					10.4	
		PLA–copper					1.82	
		PLA–graphite					0.59	
		Bio-PET and Ag					10.3	
		Bio-PET and Cu					1.72	
		Bio-PET–graphite					0.51	
Self-monitoring glucose measurement (SMBG)	Lancets	Stainless steel and plastic	GWP in midpoint impact categories of the ReCiPe hierarchical method, with the glucose monitoring methods for their entire life cycle	Cradle-to-grave	1 year	7.01–9.61	1.96–3.27	Hosseinian *et al.* 2025 (ref. 9)
	Strips	Polyester/ polycarbonate and silver/gold					1.40–1.96	
Continuous glucose monitoring devices (CGM)	Leaflet	Paper				27.73–34.62	10.73–13.59	
	Plastic parts	Plastic					7.76–12.46	
	Printed circuit boards	Fiberglass, copper, and epoxy resin					3.05–5.54	

[a] Polyethylene terephthalate – PET, polylactic acid – PLA, high-density polyethylene – HDPE, carbon nanotubes – CNTs.

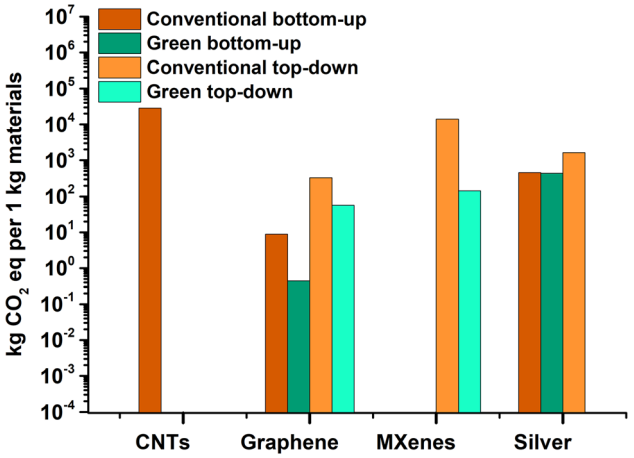

Fig. 1 Comparison of life-cycle GWP per 1 kg material produced: carbon nanotubes (CNTs), graphene, MXenes, and silver. Detailed comparison tables are available in the SI. Note the logarithmic scale of the *y*-axis. The functional units differ across the original studies, and the functional units for CNTs (1 g), graphene (1 g), and MXenes (1 g) were linearly scaled up to match the functional unit for silver (1 kg).

analyte into an electrochemical signal, with the working electrode playing a crucial role in the detection process.

Because glucose is not inherently electrochemically active, the working electrode is coated with a reagent layer containing glucose oxidase or glucose dehydrogenase and possibly a mediator. This layer facilitates the oxidation of glucose, enabling electron transfer to the working electrode. The composition of the reagent layer is outside the scope of this review, as no alternatives exist, and biological reagents are typically non-recoverable. Moreover, LCA studies of glucose strips typically focus on plastics and metals; mediators are often excluded due to their low mass and limited data availability. However, there is a need for green-chemistry approaches in mediator design: the use of biodegradable, non-toxic, or renewable mediators and a better understanding of end-of-life degradation and toxicity profiles.

The electrodes are printed or deposited onto a substrate that provides mechanical support and defines the strip's physical structure. A transparent or semi-transparent polymer film typically seals the top, protecting the internal components while allowing the sample to be visible. Contact pads at one end of the strip form the electrical interface with the glucose meter.

In this paper, we focus specifically on the working electrode and provide insights into the reference electrode, strip manufacturing processes, and considerations for recyclability.

3.2 The materials of the working electrode and their alternative synthesis methods

The core component of the sensor's function is the working electrode. Currently, the state-of-the-art materials for commercial implantable glucose sensors are either platinum or gold, which are critical raw materials, whereas strips use working electrodes primarily based on carbon-based materials and mediators (such as ferricyanide). Overall, a previous study shows that the environmental impact of the electrode materials was several orders of magnitude higher than that of the substrate materials.[26]

Various nanomaterials, polymers, and mediators have been explored for surface functionalization of the working electrodes. The environmental impact of screen-printed electrodes has been compared across materials, including platinum, gold, silver, copper, carbon black, and carbon nanotubes.[14] Among these, carbon black was found to have the least impact on the environment, while the noble metals had the highest impact.

The primary motivation for seeking alternative working electrode materials for test strips is to address the sustainability, performance, and cost limitations of currently used materials—particularly given their widespread use and the growing demand for self-monitoring technologies. Furthermore, next-generation sensors aim to detect multiple analytes, operate in wearable or implantable formats, and function without the need for enzymes. This requires tunable, robust, and multifunctional electrode materials not limited by the drawbacks of current materials.

The performance of electrochemical sensors, in terms of limit of detection (LOD), linear range, and sensitivity, varies across different sensing materials and analytes. Several review studies provide an overall comparison of these parameters. For example, CNT-based dopamine sensors generally exhibit LOD from nanomolar to micromolar levels (0.00013–0.57 μM), with a linear detection range spanning 0.03 to 1950.2 μM and possess sensitivity between 0.046 and 2.197 μA μM^{-1} cm^{-2}.[30] On the other hand, the LOD for CNT-based glucose sensors ranges from 0.31 to 3.9 μM, and linearity spans from 0.025 to 1 mM, with sensitivity between 2.1 and 11.5 μA mM^{-1}.[31] Recent reviews and the data presented in Tables S1 and S2 indicate that direct comparisons of sensor performance are challenging due to the prevalence of hybrid materials and the use of varied transduction techniques across studies. The adoption of green synthesis techniques does not appear to significantly affect sensor performance. Further research is required to optimise the composition of sensing materials produced *via* environmentally sustainable methods, based on a comprehensive understanding of each material's properties.

When researchers propose alternative working electrode materials in the name of sustainability, justifications are simplified. For example, the inclusion of nanoparticles is claimed to reduce reliance on critical raw materials. This reasoning is similar to suggesting that carbon is sustainable simply because it is abundant. However, nanomaterials are often produced through chemical or physical processes that negatively impact the environment, human health, and natural resources.[32] Especially, the synthesis of carbon-based nanomaterials involves using precursors such as unsaturated and saturated hydrocarbons taken from fossil fuels and heavy metals as catalysts. The synthesis of CNTs typically requires 1 gram of catalyst to produce several grams of CNTs.[33] In contrast, the mass of metallic catalysts used in chemical vapor deposition (CVD) of graphene is generally not reported, as the metal serves as a reusable substrate rather than being consumed stoichiometrically. Here, we examine alternative materials for the working electrode and evaluate their environmental impacts.

While LCA is a powerful tool, most LCAs of manufactured nanoparticles lack comprehensiveness, as they primarily focus on analyzing nanomaterials in input flows (*e.g.*, material, energy, and water consumption), while often neglecting output flows, particularly those associated with environmental releases.[34] Another challenge is that many novel nanomaterials have not yet been used in industrial-scale applications. For example, kilogram-scale synthesis of $Ti_3C_2T_x$ MXene consumes about one-ninth the energy per kilogram compared to gram-scale production.[35] Overall, LCA or the estimation of the energy demands of industrial-scale production of novel materials that are currently synthesized only in gram quantities remains challenging.

In the following subchapters, we cover alternative nanomaterials as electrochemical (bio)sensing transducers and assess them from environmental aspects. The focus is on carbon-based nanomaterials, MXenes, and metal nanoparticles. The list is not exhaustive but includes commonly discussed materials and material groups.

Overall, nanomaterials are synthesized using two approaches: top-down and bottom-up. Fig. 2 shows that the top-down method involves breaking down larger structures into nanoscale materials, while the bottom-up approach focuses on building larger nanostructures from smaller atoms or molecules. While both reducing agents and etching agents are used in top-down and bottom-up approaches, the most used environmentally critical agents in each approach are illustrated in Fig. 2. The selection of synthesis methods for working electrode materials is influenced by factors such as precursor availability, facility capabilities, environmental considerations, and economic feasibility. A thorough understanding of each synthesis process is essential for developing more sustainable routes. In recent years, efforts to enhance performance have led to the exploration of novel sensing materials. In this review, we assess the environmental aspects of producing the materials used in working electrodes and compare the GWP of their production at the lab scale.

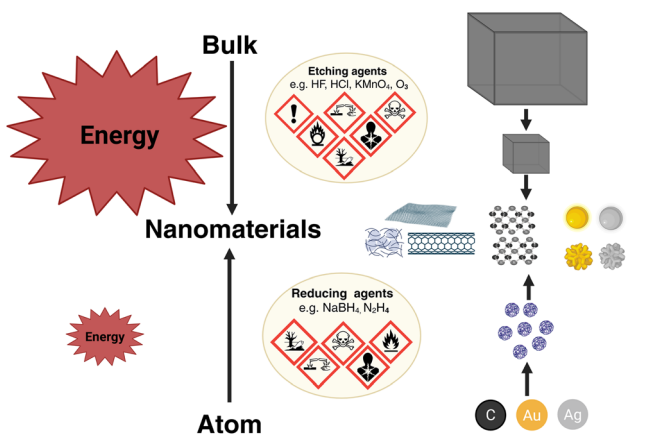

Fig. 2 Schematic comparison of top-down and bottom-up synthesis routes for carbon nanomaterials, MXenes, and metal nanoparticles, showing typical hazardous reagents and relative energy requirements. The energy ratios are presented for conceptual illustration and have not been experimentally verified. Created in BioRender. Seo, J. (2026) https://BioRender.com/p42v106.

Table 2 summarizes the environmental aspects of top-down and bottom-up synthesis routes for carbon nanomaterials. Tables 3 and 4, presented in the following subchapters, provide more detailed insights into MXenes and metal nanoparticles, respectively. In the tables, we focus on green chemistry as an alternative synthesis route, which involves immediate actions to reduce environmental impacts. In this review, we distinguish the term 'green' from cases in which actions involve direct and general efforts to reduce environmentally negative impacts. On the other hand, we used the term 'sustainable' in a big-picture context, considering the long-term environmental impacts of producing the strips, including all materials involved. To be precise, green practices may reduce the negative impact on standard products, but the remaining impacts may still be negative, making sustainable products difficult to obtain because we need to consider all aspects.

3.2.1 Carbon nanomaterials

3.2.1.1 Carbon nanotubes. The exceptional sensitivity of carbon nanotubes (CNTs)' electronic properties to surface-adsorbed molecules, combined with their extremely high surface area, makes them an ideal platform for developing ultra-miniaturized chemical and biological sensors.[74] Moreover, CNT-based enzymatic glucose sensors are highly regarded for their nanoscale dimensions and exceptional chemical, thermal, and mechanical stability, which make them ideal matrices for enzyme immobilization.[75]

CNTs are synthesized using either bottom-up or top-down approaches. The choice of synthesis technique typically depends on the availability of resources and demand. Low dispersibility plays a significant role in the industrial-scale synthesis of CNTs.[76] Furthermore, solid, liquid, and gaseous carbon precursors are commonly used in various processes, all of which are petroleum-based and non-renewable. Solid precursors, such as coal and graphite, are widely employed in arc discharge and laser ablation to synthesise CNTs. One of the challenges associated with these processes is the significant amount of byproducts produced during synthesis, as well as the high energy consumption required. In CVD, the most widely used technique for synthesizing CNTs, metal or metal oxide catalyst particles serve as seeds for growing CNTs.[77] A previous study examined life-cycle greenhouse gas emissions associated with different CVD methods, focusing on two reactor types: on-substrate and fluidized-bed reactors.[78] Their findings indicated that the life cycle GWP from the on-substrate CVD method was 28.55 kg CO_2e per g CNTs, which was significantly higher than 0.48 kg CO_2e per g CNTs from the fluidized-bed CVD methods. However, the downstream processing of CNTs remains unclear, as their applications are limitless. Another LCA study on overall synthesis processes of multi-walled and single-walled CNTs showed that grid electricity accounted for the majority of the environmental impacts.[79] The results indicate that the global environmental footprint of CNTs and their products depends on the synthesis processes used, which can be reduced by up to 88% through different scaling methods worldwide. Environmental challenges in synthesizing CNTs can be partially

Table 2 Environmental considerations of top-down and bottom-up techniques for carbon nanomaterial synthesis[a]

Approach	Bottom-up	Top-down
Essential factors for alternative pathways guided by Green Chemistry principles of Anastas and Warner[36]	• Catalytic reagents should be as selective as possible	• Use of biobased precursors
	• The precursors should be renewable and biodegradable, and resource depletion should be avoided. The chemicals should turn into non-toxic derivatives	• Harvesting the excess heat and limiting energy usage
	• Maximising the incorporation of the atoms of the reactants into the products	• Synthesis at room temperature
	• Organic solvents can be replaced with safer solvents such as supercritical fluids, water, and ionic liquids	• Development of reactions that generate minimal byproducts or produce byproducts that are readily degradable
		• Overall, the reactions should be minimally toxic, and if they cannot be avoided, real-time monitoring of the pollution should be considered
Sustainability & scalability	• Using green precursors and solvents can make the process more sustainable	• They are often less sustainable unless green energy sources and waste reduction strategies are implemented
	• They are suitable for precise nanostructures in sensors and electronics; CVD offers strong industrial scalability, but green precursors can pose challenges in catalyst compatibility and reproducibility	• It is easier to achieve rapid initial scale-up, but it is less environmentally favorable due to potentially higher costs
Techniques	CVD, electric arc discharge, sol–gel process	Sputtering, laser ablation, electrospinning
Common products	Carbon nanotubes, carbon nanofibers, carbon dots	Graphene oxide, graphene
Energy consumption	Lower	Higher because most of the energy is converted to heat, and the products are of lower purity, produced with relatively low deposition rates
Material waste	Lower, but CVD involves toxic gaseous byproducts	Higher
Hazardous reagents	• Petroleum-based precursors (*e.g.*, methane,[37–40] ethylene,[41,42] and ethanol[43,44])	• Dispersion solvents (*e.g.*, DMF[45] and NMP[46,47])
	• Organic solvents (*e.g.*, toluene,[48,49] DMF,[50–52] and THF[53,54])	• Chemical oxidants/reductants (*e.g.*, $KMnO_4$,[55,56] O_3,[57] $KClO_3$,[58,59] and hydrazine[60])
	• Heavy metals or their hybrids as catalysts (*e.g.*, Fe,[61–63] Co,[64,65] Ni,[66,67] Cu,[61,68,69] and Ir[70])	• Surfactants/polymers/stabilisers (*e.g.*, SDS,[71] SDBS,[72] and CTAB[73])

[a] Cetyltrimethylammonium bromide – CTAB, dimethylformamide – DMF, *N*-methyl-2-pyrrolidone – NMP, tetrahydrofuran – THF, sodium dodecyl benzene sulfonate – SDBS, sodium dodecyl sulfate – SDS.

addressed by using bio-based precursors. One of the earliest reported renewable precursors is camphor, which is derived from plants.[80] Since then, various biomasses have been utilised, including coconut shell,[81] olive,[82] palm oils,[83] biodiesel oil,[84] and grass.[85,86] In general, as more sustainable synthesis routes, a perspective by Pedersen *et al.* (2021) suggests a sustainable 'green' CVD philosophy, including the use of greener precursors, the production of fewer by-products, the utilization of renewable energy in the processes, and the harvesting of excess heat.[87] Additionally, one of the biggest challenges in the synthesis of CNTs is optimisation of multiple parameters such as catalyst, temperature, pressure, and carbon feedstock.[88] These parameters must be thoroughly studied to obtain CNTs with desired properties to scale up the synthesis of CNTs with sustainable approaches. For example, large-scale production can reduce feedstock requirements by 96%, carrier gas by 62%, catalyst and deionized water by 50%, and electricity requirements by 87%, resulting in an 88% reduction in environmental impact.[79,89] In this study, CVD was identified as the most impactful on the environment. In contrast, the high-pressure carbon monoxide reaction was the least impactful for single-walled CNTs, while the arc discharge process was the least impactful for multi-walled CNTs.[79] However, the environmental impacts of industrial sectors did not correspond to their shares, as they employ specific processes for the application of CNTs. Machine learning methods can be useful for optimizing experimental parameters, including precursors, catalysts, and temperatures.[88] Machine learning methods, combined with experimental testing, can accelerate the solution of challenges by providing a deep understanding of the sustainable industrial-scale synthesis process.

3.2.1.2 Graphene. Along with CNTs, graphene is a type of graphite material. Graphene and graphene-based nanomaterials are increasingly favored for their high surface area, excellent electrical conductivity, and rapid electron-transfer

rates.[90,91] They are also effective at immobilizing various biorecognition elements.

Graphene is synthesized through both top-down and bottom-up approaches. Top-down approaches include the exfoliation of graphite, while bottom-up approaches include CVD, epitaxial growth, and laser ablation.[92] The mechanical exfoliation of graphite to produce graphene popularized its production. Subsequently, electrochemical exfoliation was developed to synthesise graphene from graphite, which is beneficial for efficient scaling up.[93] Electrochemical and mechanochemical reduction of graphene oxide is widely used to produce graphene, although toxic reducing agents are often necessary. As shown in Table S3, production of graphene by conventional top-down techniques, such as the chemical oxidation process followed by chemical/thermal reduction, yields 0.143 kg and 0.080 kg CO_2 per 1 g of graphene produced, based on the lowest-impact production scenarios.[94] Along with electricity consumption, which is the main factor contributing to all other impact categories, chemical consumption was also found to be a second contributor to environmental impact. Typically, to produce graphene oxide, top-down approaches such as chemical and electrochemical exfoliation are employed. Hummer's method was developed to produce graphitic oxide from graphite. This method involves using strong inorganic acids and potassium permanganate, of which Mn^{2+} is toxic and can produce unstable intermediates.[76] Subsequently, several methods were introduced, including minor modifications to Hummer's method. The focus of improved methods is typically on increasing yield, with environmental impacts often not being considered. However, some studies focused on the environmental aspect of the method. For example, to mitigate the negative effects of chemicals, a synthesis method for graphene oxide using the oxidant K_2FeO_4 was studied.[95] The study showed that this method avoids the heavy metal pollutant Mn^{2+} and toxic gases while also allowing for the recycling of sulfuric acid in the large-scale production of graphene oxides. Similarly, in the context of green production, several studies have utilized natural precursors to synthesize graphene oxide. For example, cellulose from corncobs is used as a green precursor and treated with alkalization, bleaching, and pyrolysis.[96] Waste materials, such as coconut shells,[97] rice bran,[98] and used polyethyleneterephthalate (PET),[99] were used as carbon sources. Furthermore, natural reducing agents have attracted interest for the more sustainable production of graphene. For example, reducing agents derived from cloves,[100] lemon extract,[101,102] and aloe vera[103,104] have been reported as green alternatives.

LCA studies are crucial for optimizing the environmental impacts of producing graphene at a commercial scale. An LCA study of different synthesis routes for graphene demonstrates that when lab equipment is fully utilized, the chemical oxidation process, followed by thermal reduction, has the lowest environmental impact for producing large quantities of graphene.[94] Notably, another LCA study of graphene production using waste-based feedstocks (industrial coal tar pitch, rice husk, plastic waste, and paper waste) showed that the energy required to convert the feedstocks into precursors has a significant environmental impact.[105] Furthermore, an LCA study of graphene sensors reveals that copper foil significantly contributes to primary energy consumption, accounting for over 25% in the baseline scenario for graphene production.[106] Therefore, recycling copper foil and optimizing processing methods, such as a transfer method without iron nitrate, can support more sustainable production of graphene transparent electrodes. In terms of material production, it was confirmed that the transition to renewable energy reduces GWP by 20% in electricity consumption and by 20% in KOH use.[107] The usage of KOH is found to be a notable contributor to the environmental impact. With the scaling up of graphene production, thermal exfoliation is roughly 68 times more environmentally friendly than the oxidation–reduction method.[108] The results showed that electricity is a hotspot for graphene production, so decarbonizing electricity is a main direction for mitigating the environmental footprint. A study noted potential trade-offs between graphene yield and process energy consumption. For example, a method that yields 33% has twice the environmental impact of a method that yields 25%.[94] This indicates that further optimization of experimental parameters, such as applied potentials and electrolyte selection, is needed for electrochemical exfoliation. Likewise, an artificial neural network has shown the potential to learn to synthesize high-quality graphene in a scalable manner, requiring minimal initial input.[109] This demonstrates the network's ability to learn and adapt over time, leading to progressive improvements in graphene quality. Beyond identifying critical environmental factors and implementing improvements, it is essential for scalable approaches to align with LCA studies and utilize AI-driven methods.

3.2.1.3 Carbon nanofibers. Carbon nanofibers (CNFs) exhibit high sensitivity and selectivity for target molecules, making them an effective platform for biosensors.[110] While they share structural and property similarities with CNTs, CNFs are easier to produce and provide enhanced functionality.[111,112] CNFs are typically synthesized using bottom-up approaches, such as catalytic thermal CVD growth and electrospinning, followed by heat treatment.[113] Large-scale synthesis of CNFs is typically achieved through CVD methods, specifically plasma-enhanced CVD, which employs metal particles as catalysts, and hydrocarbon and H_2 as reaction gases.[114,115] In CVD growth methods, various metals, such as iron, cobalt, and nickel, or metal alloys, dissolve carbon and form metal carbides. Carbon sources such as methane, carbon monoxide, synthesis gas (a mixture of hydrogen and carbon monoxide), ethyne, and ethene are employed at temperatures ranging from 700 to 1200 K.[116,117] Electrospinning is another well-established technique to synthesize CNFs using electrostatic forces. In this technique, polymers or polymer blends should be dissolved in suitable solvents, which may be toxic and require high-temperature treatment.[118,119]

One of the more sustainable synthesis routes involves using renewable bioresources such as lignin,[119] cellulose nanocrystals,[120] bamboo,[121] biomass tar,[122] and coal tar.[123] Additionally, recycling polymers, such as PET[124] and polystyrene,[125] has shown potential to produce high-performance CNFs. Another example of green synthesis is the utilization of the greenhouse gas CO_2 as a carbon source.[126] This study introduces a tandem

electrocatalytic–thermocatalytic strategy for CNF production, combining the co-electrolysis of CO_2 and water into syngas (CO and H_2) followed by a thermochemical process at mild conditions (370–450 °C, 1 atm). The life-cycle energy and environmental impact analysis of CNF production reveals that the energy required to produce CNFs is 13 to 50 times higher than that needed for aluminum, steel, and polypropylene on an equal mass basis. The life cycle energy requirements for methane-based CNFs are roughly 3 times higher than those of benzene-based CNFs. With methane feedstock, recycling unreacted hydrocarbons and 90% of the hydrogen stream decrease the energy requirements by 1.3%. If CNFs are in a polymer matrix, their production requires 1.6 to 12 times more energy than steel production.

Additionally, the impact assessment methods, including midpoint and endpoint, reveal that CNFs may have a greater overall environmental impact, although they demonstrate lower ecotoxicity compared to traditional materials.[116,127] Based solely on these most relevant studies, we conclude that producing 1 kg of CNFs may result in roughly 600 kg of CO_2, similar to the GWP of silver production, as shown in Tables S3 and S4. However, to the best of our knowledge, there have been limited LCA studies on the production of CNFs. Thus, more LCA studies on conventionally produced CNFs, green produced CNFs, and their applications in disposable biosensors are still needed.

3.2.1.4 Carbon dots. The optical and surface properties of carbon dots (CDs) make them attractive materials for electrochemical and optical biosensor applications. CDs offer several advantages, including low toxicity, high biocompatibility, and easy functionalization.[128] CDs are synthesized using top-down approaches, such as laser ablation, electrochemical oxidation, and arc discharge, as well as bottom-up approaches, including hydrothermal (or solvothermal), microwave-assisted, and or calcination methods. Bottom-up approaches, especially the solvothermal method, are commonly used because top-down approaches require harsher experimental conditions and more expensive materials.[129,130] Typically, the synthesis of CDs is energy-intensive; therefore, the green synthesis should prioritize lower-energy methods. Overall, the green synthesis of CDs is carried out using hydrothermal, microwave, and dry-heating methods.[131] An LCA study compared six bottom-up methods for synthesizing CDs, including hydrothermal and microwave-assisted synthesis using citric acid, a common carbon precursor.[132] The results indicate that electricity usage accounts for 66.5% of the environmental impact in hydrothermal synthesis, whereas citric acid has the greatest environmental impact in microwave-assisted synthesis. In the industrial-scale hydrothermal synthesis of CDs, precursors were found to be a critical point for environmental impacts, with citric acid accounting for 58.8%, followed by urea (29.4%), rather than the electricity used (11.4%). For example, using glucose as a carbon source decreased all impact categories by 15%. Another LCA study compared three representative bottom-up approaches to synthesize CDs using citric acid and urea as precursors.[129] The results show that microwave-assisted synthesis has the lowest environmental impact and should be the preferred method, with calcination as the next option. Moreover, it has been shown that using an alternative carbon source, such as glucose, can further improve the environmental impact of industrial-scale synthesis.[133] An LCA study suggested that biomass-derived CDs from eucalyptus leaves can reduce GWP up to 31% on average,[134] but none of the LCA studies shown in this review reported absolute values for GWP. The researchers presented the values in relative contributions of the different inputs. Thus, it is difficult to compare with other materials based on the LCA studies.

The future trajectory of CDs derived through green synthesis or from bio-wastes is defined by their convergence with sustainable synthesis and their unique functional properties. The core promise lies in utilizing eco-friendly, waste-derived precursors, which eliminates the need for harsh chemicals and promotes a circular economy in advanced materials fabrication. Several studies have reported on synthesising CDs from plant biomass precursors, including flower extracts,[135] lotus root,[136] coconut petiole residues,[137] lignin,[138] and cassava pulp.[139] The inherent structure of these CDs lends itself to powerful applications, particularly in electrochemical properties and sensing. Researchers are actively exploring the excellent conductivity and surface activity of these materials for high-performance applications, such as more sustainable batteries and efficient electrocatalysis in green chemistry.[140] This superior electrochemical profile is concurrently being leveraged to develop highly sensitive, advanced sensors for crucial areas like environmental monitoring, ensuring food safety, and early-stage healthcare diagnostics.

Ensuring consistent CD properties through green synthesis methods for biosensing applications can be challenging. Nevertheless, a recent review found that CDs, among carbon nanomaterials, could be a promising candidate for applying the twelve principles from the Environmental Protection Agency in agricultural applications.[141] To address the challenges in green synthesis methods, it is necessary to gain a deeper understanding of how parameters in both traditional and green synthesis methods affect the resulting properties of CDs and their performance in biosensor applications. Machine learning in the synthesis of CDs shows potential in predicting the properties of CDs and identifying the optimal input parameters for synthesising CDs.[142] However, optimal machine learning models can vary depending on input and target feature conditions. Thus, future research using machine learning methods for synthesis should aim to identify the true optimal parameters for CD synthesis and their performance, either theoretically or numerically. This can enhance the overall scalability and sustainability of CD synthesis methods.

3.2.2 MXenes. MXenes, a class of two-dimensional transition metal carbides, have garnered significant attention due to their unique properties and potential applications in various fields, including energy storage, electronics, and sensing. MXenes' exceptional electrical conductivity and adjustable surface chemistry distinguish them from conventional materials. For biosensors, MXenes are typically used as carriers for biomolecules, and the immobilization of biomolecules onto the MXene surface is generally achieved using gold nanoparticles or *via* electrostatic adsorption. A review suggests that the direct

chemical coupling between biomolecules and MXene is more valuable, considering the stability of biocomposites and the abundant surface chemistry of MXene.[143] Among the different types of MXenes, titanium carbide-based MXenes ($Ti_3C_2T_x$) have emerged as promising materials for electrochemical applications in the biomedical field, including a critical diagnostic tool for glucose sensing.[144] MXenes are typically synthesized by the top-down approaches, which involve a multi-step process that begins with the etching of MAX ($M_{n+1}AX_n$) phases, layered ternary compounds consisting of a transition metal (M), an early transition metal (A), and a p-block element (X). Table 3 presents the overall environmental aspects of MXenes synthesis routes. As MXene production scales up to commercial levels, it is crucial to address safety concerns, particularly during MAX phase synthesis and etching processes. Dust ignition, runaway reactions, and exposure to toxic chemicals are significant hazards. Using alternative milling methods can mitigate dust-related risks in MAX phase synthesis. However, the etching process, especially with HF, poses significant challenges due to the risk of releasing corrosive materials and toxic fumes. Proper handling, protective equipment, and thorough washing are essential to minimize HF exposure and its long-term toxicity. To mitigate the risks associated with HF, researchers have explored alternative, less hazardous etching methods, including alkali treatment, electrochemical methods, Lewis acid-molten salt approaches, and hydrothermal methods. In addition to sonication for exfoliation, organic solvents such as choline hydroxide, tetrabutylammonium hydroxide, *n*-butylamine, and dimethyl sulfoxide have been investigated for the synthesis and exfoliation of MXenes. Multilayer MXenes can be swelled in these solvents and further sonicated to yield colloidal particles. Centrifugation then produces homogeneous MXene nanosheets.[144]

When LCA was conducted to evaluate the cumulative energy demand and environmental impacts of lab-scale synthesis of $Ti_3C_2T_x$, the most extensively studied MXene composition, the results indicated that electricity consumption during laboratory synthesis accounts for more than 70% of the total environmental impacts.[35] The choice of source material also influenced the LCA outcomes. In the studied example, one synthesis route utilized titanium dioxide (TiO_2) as the titanium source, whereas the other used pure titanium, consistent with the rest of the LCA presented in earlier sections. The Ti_3AlC_2 MAX phase system employing TiO_2 exhibited significantly higher adverse impacts in four key categories—ecotoxicity, carcinogenicity, acidification, and non-carcinogenic toxicity—while showing substantially lower impacts only in ozone depletion. Although the use of chemicals was found to be less impactful than electricity, for the synthesis of $Ti_3C_2T_x$ MXene, titanium was the most impactful, accounting for 75%. Aluminium accounted for 15%, while LiCl made up 10%. As shown in Tables S3 and S4, a lab-scale synthesis of MXene results in 428.10 kg of CO_2 per 1 kg $Ti_3C_2T_x$ MXene produced by a conventional synthesis method, 1.44 kg, and 7.54 kg of CO_2 per 1 g of $Ti_3C_2T_x$ MXenes produced by more sustainable methods. Because MXenes are currently synthesized only at a lab scale, these materials are difficult to compare with 1 kg of metals manufactured at an industrial scale, such as aluminum (23.0 kg) or copper (8.75 kg). Notably, depending on the modeling choices, the same synthesis method yields completely different values. For example, the synthesis path with a GWP of 428.10 kg CO_2 eq. was recalculated in another study.[151] It reported 14.0 kg of CO_2 per 1 g of MXenes produced, the most environmentally impactful among various synthesis paths. While both studies used cradle-to-gate approaches, the second study also considered upstream material processing and the lab infrastructure. In this comparative

Table 3 Environmental considerations of top-down techniques for MXene synthesis

Approach	Top-down
Essential factors for alternative pathways guided by Green Chemistry principles of Anastas and Warner[36]	• Use of less toxic etchants instead of volatile and dangerous HF • Etchant recycling can be considered • Energy requirements should be recognised and minimised. Synthesis should be carried out at room temperature
Scalability & sustainability	• According to Hansen *et al.* (2024),[145] $Ti_3C_2T_x$ MXenes are safe and sustainable when applying the Safe and Sustainable by Design (SSbD) framework (European Commission): (1) reviewing health, environmental, and safety information; (2) characterising MXenes transformation/dissolution in different media; (3) conducting (eco) toxicological experiments, and (4) completing a prospective life-cycle assessment • Toxicity with fluoride use limits the scalability of MXene synthesis
Techniques	Selective etching of MAX phases (*e.g.*, HF or *in situ* HF etching)
Precursor	MAX phase ceramics (Ti_3AlC_2, Nb_2AlC, V_2AlC, *etc.*)
Common products	$Ti_3C_2T_x$, Nb_2C, V_2C MXenes
Energy consumption	The requirement for high-temperature conditions leads to an energy-intensive process (etching, washing, delaminating, and drying steps)
Material waste	• Large volumes of acidic waste from HF/LiF/HCl • Under or over-etched MAX phase • Metal waste of Ti and Al, and solid particulates such as C
Hazardous reagents	• Highly toxic etchants (*e.g.*, HF,[146–148] LiF/HCl[149,150]) • Highly flammable powders like aluminium and titanium carbide or graphite

LCA study,[151] the greenest synthesis path was identified as the first reported synthesis of $Ti_3C_2T_x$,[146] although it employs a 50% HF solution in excess.

Systematic approaches and standardized results from LCA studies are needed to recommend a safer, more sustainable synthesis pathway in the long term. In general, green methods for MXene synthesis involve renewable energy, energy-efficient procedures, recycled precursors, and milder etchants. For example, a hydrothermal synthesis method using less toxic etchants, such as $NaBF_4$ and HCl, in a closed system provides a more energy-efficient process.[152] Another study demonstrates a low-temperature molten-salt etching method for the large-scale synthesis of diverse MXenes within minutes, using NH_4HF_2 as the etchant.[153] Furthermore, several studies have shown that microwave-assisted hydrothermal synthesis, a variant of conventional hydrothermal synthesis, offers efficient energy consumption, shorter synthesis times, and a potential for HF-free synthesis.[154–156]

3.2.3 Metal nanoparticles. Metal nanoparticles (MNPs) have found widespread use in biomedical applications, including glucose biosensors. By increasing surface area and facilitating electron transfer between enzymes and electrodes, MNPs enhance detection signals and reduce the need for raw materials. Their magnetic properties enable the assembly of enzyme-bound nanoparticles on electrode surfaces, and they can even form conductive wires.[157] The integration of nanomaterials, including various MNPs like gold, platinum, silver, iron, zinc, copper, palladium, iridium, and their alloys, has contributed to the miniaturization of glucose biosensors. These MNPs serve as modifiers, labeling agents, or immobilization agents, further improving sensor performance.[158] Despite their potential, the widespread use of MNPs necessitates rigorous consideration of their long-term environmental and health impacts. The concern lies in their potential toxicity to non-target organisms, their bioaccumulation in ecosystems, and their ability to penetrate human tissues, which may cause oxidative stress and inflammation.[159] Given that the long-term, chronic effects of exposure are not yet fully understood, future research must focus on improved characterization, understanding MNP fate and transport, and developing robust methods for controlling their release into the environment through sustainable design and safer alternatives.

Currently, MNPs can be produced through two primary approaches: top-down methods, which rely on machining or etching a bulk material, or bottom-up methods, which involve controlled self-assembly from the atomic level upwards. Table 4 presents the environmental aspects of various top-down and bottom-up methods for synthesizing MNPs, along with green routes for the synthesis of MNPs. The increasing prioritization of green synthesis approaches for MNPs represents a critical step in mitigating the environmental and health risks associated with conventional chemical methods. This methodology achieves significant risk reduction by prioritizing the use of non-toxic, biocompatible materials, such as renewable plant extracts or microorganisms, as the primary reducing and stabilizing agents. This direct substitution eliminates the need for hazardous and toxic reagents, resulting in substantial environmental benefits, including reduced toxic waste generation and lower energy consumption due to milder reaction conditions.[160] Consequently, green synthesis yields MNP products that are inherently safer and more biocompatible. This reduced toxicity not only lowers the risk of adverse health effects, such as oxidative stress or inflammation,

Table 4 Environmental considerations of top-down and bottom-up techniques for metal nanoparticle synthesis

Approach	Bottom-up	Top-down
Essential factors for alternative pathways guided by Green Chemistry principles of Anastas and Warner[36]	• It is advisable to avoid using toxic reducing agents whenever possible. Green alternatives to these reducing agents include natural antioxidants, enzymes, or polysaccharides. Biopolymers, plant polyphenols, and proteins can serve as stabilisers	• Natural surfactants, ionic liquids, and biodegradable polymers can be used as stabilisers • Energy requirements should be recognised and minimised. Synthesis should be carried out at room temperature
Sustainability & scalability	• Scale-up is easy, for example, when using fungi as a reducing agent, but the resulting nanoparticles can be produced in variable sizes • Plant extracts are favourable for bulk production, and byproducts are eco-friendly	• Less sustainable due to toxicity from reagents and higher energy consumption • Mechanochemical routes are scalable for bulk powders, but irradiation methods are harder to scale industrially
Precursor materials	Metal salts (*e.g.*, $AgNO_3$, $HAuCl_4$, $FeCl_3$)	Bulk metals (*e.g.*, Ag, Au, Cu, fe)
Common products	Ag, Au, pt, Fe_3O_4 nanoparticles	Ag, Au, Cu, Fe nanoparticles
Techniques	Physical or chemical vapor deposition, chemical reduction, sol–gel, spray pyrolysis, biosynthesis	Laser ablation, ball milling, ion sputtering
Energy consumption	Lower	Higher
Material waste	Byproducts that cause aquatic toxicity and air pollution (*e.g.*, nitrate and nitrogen oxide[161,162])	Organic chemicals and numerous additional chemicals are used in post-processing procedures
Hazardous reagents	• Most precipitated MNPs need stabilising reagents like polymers, surfactants, reducing agents (*e.g.*, $NaBH_4$,[163,164] and hydrazine[165,166]), and metal coordination compounds • Toxic precursors are used	• These processes need organic solvents (*e.g.*, ethanol,[167,168] methanol,[169] and toluene[170]) and etching agents (*e.g.*, HNO_3 (ref. 169) and $FeCl_3$ (ref. 171 and 172))

upon human exposure but also enhances the suitability of these nanomaterials for sensitive applications, including advanced biosensing, drug delivery, and water treatment. By aligning with core green chemistry principles, this sustainable approach ensures the final materials are cleaner, making them the preferred, eco-friendly alternative for the future of materials science and nanomedicine.

Several studies applied LCA to evaluate the environmental impact associated with the production of MNPs. A study shows that the bulk silver production itself accounts for 90% of the environmental impact in nearly every category.[173] Typically, chemical reduction methods are preferred for producing AgNPs. Interestingly, when the chemical reducing agent is replaced with soluble starch, the GWP is 434 kg CO_2 per 1 kg of AgNPs produced, which is similar to that of other synthesis routes. Verification through LCA is necessary to determine which synthesis route is more sustainable, as focusing solely on green reagents may be misleading. Production of silver particles by flame spray pyrolysis has the highest environmental impact, with a GWP of 543 kg CO_2 eq. per 1 kg of AgNPs produced (Table S3). Another LCA study identified methodological gaps and variations in system boundaries, reporting that flame spray pyrolysis can emit approximately 1650 kg CO_2 per 1 kg of AgNPs.[174] Given methodological differences and a lack of standardization, direct comparison of results from LCA *studies* remains challenging, underscoring the need for consistent methodologies.

A study using recovered secondary sources demonstrates that hydrometallurgical processing is the most suitable and widely used method for the recovery and synthesis of nanoparticles.[175] However, the synthesized metals from recycled materials can vary in size and shape, which can limit the applications of MNPs. Further research on using mixed stabilizing agents or combining surfactants may help improve the consistency of the resulting nanoparticles. As previously stated, plant-mediated synthesis of gold and silver offers a promising green alternative. For example, *Plumeria alba* and various medicinal herbs can serve as reducing agents and encapsulating agents.[176–178] The use of plant extracts for the synthesis of MNPs offers enhanced size uniformity and biocompatibility suitable for biomedical applications, although there are challenges in optimizing parameters like polydispersity index and understanding the relationship between salt concentration and yield of MNPs.[179,180]

3.3 Reference electrode

Ag/AgCl is the most commonly used reference electrode in miniaturized devices due to its stability, simple construction, low cost, disposability, and reliable performance.[181] However, to achieve these performance characteristics, commercial inks contain a high concentration of silver and silver chloride, with over 60% of the ink made up of metal nanoparticles.[182] Table 1 indicates that AgNPs in sensors result in the highest environmental footprint. Previous research has demonstrated that environmental impacts can be reduced by improving yields and recovering silver from spent solutions.[173] However, replacing with bio-based reducing agents alone may increase environmental impacts, thereby sacrificing AgNP yields.

While many studies discussed the possibility of recycling silver components from electronic waste, only a negligible amount of silver is recycled from glucose sensors. Annually, the use of 591 billion glucose test strips results in a significant loss of silver. 0.1 g of a strip contains approximately 1.0 to 2.0 mg of silver, leading to an estimated annual silver loss of 591 to 1182 tonnes. To our knowledge, no published data currently exist regarding the leaching of silver nanoparticles, particularly from disposable biosensors. However, an LCA study of nanosilver in 15 consumer products indicates that environmental impact is driven predominantly by upstream production phases, such as silver mining and energy consumption during synthesis, rather than by the release of AgNPs during the use phase. Additionally, it reveals that silver concentration and incorporation methods in the products determine how nanosilver leaches into the environment, with non-textile polymeric samples losing more AgNPs than fibrous samples.[183] Generally, silver is rarely found in drinking water (μg L^{-1} range) as purified by point-of-use devices and distribution systems of buildings.[184] Although the toxicological database on silver is insufficient to derive a guideline value, the known adverse health effect associated with silver is argyria, a skin-darkening condition seen in humans. Respiratory issues usually arise from occupational exposure, and people may also experience breathing difficulties and stomach pain.[185] Overall, silver nanoparticles (Ag NPs) leached from glucose sensors raise concerns about their toxicity and potential health and environmental impacts.[186]

To reduce the environmental impact of reference electrodes, carbon-based pseudo-reference electrodes have been widely discussed. For example, a previous study demonstrated that SWCNTs could be used as ion-to-electrode transducers to replace Ag/AgCl transducers in solid-state reference electrodes, with polyacrylic polymers serving as the Ag/AgCl system reservoir.[187] Subsequently, activated carbon was used as pseudo-reference electrodes in measurements inside concrete, possibly serving as a pseudo-reference in the presence of a high-ionic-strength (saturated) electrolyte without redox species.[188] Graphene was also proposed as an alternative pseudo-reference electrode material that addresses certain limitations of Ag/AgCl pseudo-reference electrodes.[189] However, a limitation of carbon-based pseudo-reference electrodes is their lower conductivity relative to silver, which leads to reduced sensing performance. Therefore, a greener Ag/AgCl screen-printable ink formulation was also investigated, including a formulation with a significantly lower silver nanoparticle loading of 25%, prepared in a nontoxic organic solvent, and a biodegradable polymeric mixture of polyhydroxy ether/polyether resin (1 : 2).[182] Additionally, a study introduced a recyclable silver ink produced with bio-derived binders, green solvents, and conductive fillers derived from natural precursors, thereby reducing waste and facilitating material recovery and recyclability.[190]

3.4 Biodegradable and sustainable materials for sensor substrate

Materials play a crucial role in the development of disposable sensors that are cost-effective and sustainable, while also exhibiting excellent performance. Researchers are seeking to

enhance the performance of these sensors by utilising various materials. Disposable sensors are fabricated using inks and substrates. An LCA study shows that the mass of typical plastic substrate materials, such as PET and PLA, is 0.17 kg and 0.18 kg, respectively, which is about 10 times the mass (0.013 kg) of conductive inks in electronic components.[24] The LCA results showed that among the selected substrates, PET has the highest GWP caused by both production and incineration. Roughly, the GWPs of producing PET and PLA were found to be similar, but CO_2 emissions from PLA incineration were considered biogenic because PLA is produced from bio-based materials.

Currently, most biosensor substrates are made of non-biodegradable plastics, including polyimide, polydimethylsiloxane (PDMS), polyurethane (PU), PET, and polyvinyl chloride (PVC).[191,192] The reason for the popularity of these materials is that they are relatively cheap to produce and offer good chemical, mechanical, and processing properties. However, due to their slow rates of biodegradation, these plastics accumulate in the terrestrial and marine ecosystems as microplastics, creating long-term ecological stress to the environment.[193] New disposable sensors from inexpensive and biodegradable materials are strongly needed to address this issue.[191]

Typical biodegradable substrates for electrochemical test strips include sodium carboxymethyl cellulose (Na-CMC), polyvinyl alcohol (PVA), poly(lactic-*co*-glycolic acid) (PLGA), and polycaprolactone (PCL).[194] Other widely used biodegradable substrate materials include PLA, poly-L-lactic acid (PLLA), poly(glycerol sebacate) (PGS), and poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS).[195]

In the specific case of glucose sensors, microplastic pollution from non-biodegradable substrates remains a major challenge, as most commercially available glucose test strips use PET or other polyester-based plastics as substrates.[194] Historically, paper-based substrates have also been widely used, but this material choice has largely been replaced in modern commercial strips by plastic counterparts.[196]

Promisingly, although the commercial market for glucose test strips is currently dominated by non-biodegradable substrates, several studies have demonstrated the use of biodegradable substrates. For example, PVA/gelatin system,[194] cellulose composite material,[197] polylactic acid/polyethylene glycol system (PLA/PEG),[198] polycaprolactone (PCL),[199] PEDOT:PSS/silk,[200] and PLGA[201] have been studied as biodegradable alternatives for PET.

However, while biodegradable substrate materials are useful for reducing the microplastic pollution from disposed glucose test strips, we should also consider the environmental impact of producing these materials and fabricating the strips. A previous study evaluated the environmental impact of cotton textiles, high-density polyethylene, Kraft paper, graphic paper, glass, and ceramic as substrate materials for electrochemical sensors.[14] Rather surprisingly, among the measured materials, the biodegradable cotton textile was found to have the highest environmental impact, while the non-biodegradable high-density polyethylene yielded the lowest score. The high environmental impact of cotton stems from the cotton harvesting and manufacturing processes, which involve resource-intensive cultivation and related industrial activities. Thus, we conclude that the biodegradability of the substrate alone is not sufficient to classify the strip material as environmentally friendly, even though it is an effective way to reduce microplastic pollution from disposable glucose test strips in the ecosystem. Comprehensive LCAs are essential to evaluate the materials' overall environmental impact before such designations can be made.

Additionally, we must also highlight the importance of designing the whole strip to be biodegradable. Since the substrate is only one part of the glucose strip, other materials in the strip, such as adhesives, encapsulation layers, conductive inks, and electrodes, also affect the sensor's degradability. If only the substrate is designed to be biodegradable, the discarded sensor will undergo partial degradation, leaving behind persistent material residues, including possible microplastic or composite fragments, from the remaining non-biodegradable components. In addition, presenting glucose strips on a biodegradable substrate labeled "biodegradable sensor" may give sensor users the misleading impression that the entire strip is biodegradable. This could reduce the perceived importance of proper sensor disposal, thereby contributing to the accumulation of persistent polymer residues and microplastics in the environment, even more than current non-biodegradable glucose test strips.

3.5 Recyclability considerations

A comprehensive comparison of conventional and sustainable sensor materials should consider not only performance and carbon footprint but also degradation time and recyclability efficiency, as these parameters provide important insight into long-term environmental burden and circularity potential.

Since the glucose sensor consists of various materials (plastics, metals, and reagents), recycling the entire strip remains difficult. As a result, most publications focus on recycling only one material type from the sensor, with the other material types lost in the recycling process. Since the environmental impact of electrode materials is several orders of magnitude higher than that of substrate materials, this article focuses solely on recycling electrode materials.

Several chemical processes can be used to recover typical glucose sensor materials, such as platinum, gold, and silver. Traditional industrial-scale recycling methods of these metals are typically based on either hydrometallurgical or pyrometallurgical processing. In hydrometallurgical processing, metals are extracted from electronic waste by dissolving the metal with a leaching agent such as nitric acid. The solution is then purified and precipitated to recover the metals in usable form.[202] In pyrometallurgy, the organic matter of the electronic waste is first incinerated. Then the remaining metals are smelted and refined.[203]

Multiple studies demonstrate the use of hydrometallurgical methods for recycling disposed screen-printed electrodes. For example, a study confirmed that acid leaching can recover up to 99.8% of the palladium from glucometer test strips.[106] In another study, aqua regia was utilised as the leaching solution

to recover platinum from waste SPEs to create a functioning H_2O_2 sensor.[108] There exists even a published protocol for student laboratories, detailing how to recover platinum and silver from a screen-printed electrode using nitric acid and aqua regia. The recovered platinum can be electrodeposited onto a screen-printed carbon electrode. However, this protocol is designed for educational purposes, and issues such as process efficiency and the purity of the recovered metals are not considered.[94]

To the best of our knowledge, there are limited studies on using pyrometallurgy to recycle metals from used screen-printed electrodes. However, multiple studies exist on how to use pyrometallurgy to recover metals from electronic waste, such as discarded mobile phones,[203] used circuit boards,[204] and aged lithium-ion batteries.[205] Given that the extracted materials from spent screen-printed electrodes are comparable to those from the aforementioned types of electrical waste, we expect pyrometallurgy to be a suitable recycling option for the spent screen-printed electrodes. However, this needs an experimental validation.

Although recycling transforms electronic waste into valuable materials, the environmental impact of the recycling processes themselves must not be overlooked. The recycling process of waste materials may even have a more negative environmental impact in the short term compared to using virgin materials. For example, an LCA study on pyrometallurgical recovery of crude copper from waste printed circuit boards shows that electricity consumption accounted for 31.84–64.25% across 13 of the 18 evaluated indicators, highlighting the need for renewable energy-based power regeneration.[206] However, the results showed that substituting diesel with natural gas offers insignificant emission reductions, but waste heat recovery for power generation, with natural gas replacing diesel, reduced carbon intensity by 51.73%. A higher share of non-fossil energy in the power mix can reduce the environmental burden of the current pyrometallurgical recovery. According to current knowledge, only a limited number of studies have addressed the environmental implications of hydrometallurgical and pyrometallurgical approaches to recycling discarded sensor waste. Thus, it is challenging to evaluate whether the recycling process for disposable sensors has a positive or negative impact on the environment. Nevertheless, it is reasonable to assert that these processes carry significant environmental costs since pyrometallurgical processing requires large amounts of energy and hydrometallurgy generates substantial quantities of toxic waste from used leaching agents.[202]

However, hydrometallurgy and pyrometallurgy have been successfully used to reduce the environmental impact of electrode materials extracted from other sources of electrical waste. For instance, the GWP of metals extracted from discarded printed circuit boards was only 25.8 g CO_2 per gram of metal produced, whereas mining and refining these metals would produce 55.7 g CO_2 per gram of metal produced. However, these numbers are not entirely comparable, as the purity of the recycled metals (95%) was considerably lower than that of metals from primary production sources (99.9%), which may contribute significantly to the observed difference.[207] Furthermore, life-cycle greenhouse gas emissions of lithium hydroxide recovered hydrometallurgically from spent lithium-ion batteries were 37–72% lower than those of virgin lithium hydroxide extraction.[208] Moreover, pyrometallurgy can reduce the CO_2 emissions of lithium-ion battery materials (lithium, nickel, and cobalt) by 34.8% compared to the raw materials. However, the study also noted that hydrometallurgical recycling offers an even greater reduction in emissions (up to 55%).[209]

Thus, it is possible that the hydrometallurgical or pyrometallurgical recycling of disposed screen-printed electrodes, such as discarded glucose strips, might positively affect the environment on several indicators. In particular, hydrometallurgy appears to be a promising technology for this purpose. Nevertheless, this statement would still need experimental validation, given that, to our knowledge, no prior investigations have yet confirmed these assumptions.

3.6 Inks, binders, and strip manufacturing

For manufacturing processes for disposable sensors, a recent review highlights a circular economy approach for screen printing of electrodes.[210] One of the core aspects is the production of conductive inks from sustainable or natural sources, and second, the complete or partial replacement of potentially hazardous materials with alternatives that process enhanced environmental and economic attributes.

Based on the information gathered in this review, we prepared a decision matrix (Table 5) and Fig. 3 to select sustainable working electrode materials. The framework is not intended to provide a definitive or perfect ranking of materials; rather, it offers insight into the key factors to consider when selecting materials. In addition to electrochemical performance, it highlights important sustainability-related aspects, including scalability, environmental toxicity, recyclability, and the availability of LCA data. By bringing these criteria together, the matrix can serve as a practical guide for informed decision-making and for identifying promising new working electrode materials that balance performance with environmental and sustainability considerations. For the working electrode materials, performance was compared using Tables S1 and S2. Sustainability in terms of GWP was compared using Tables 1, S3, and S4. The scalability of the materials depends on the availability of commercially mass-produced products. Carbon nanomaterials, MNPs, and MXenes can be synthesized from recycled feedstock, though the energy required to convert waste into feedstock is considerable. Environmental toxicity compiled from existing toxicity studies.[211–213] LCA data availability is based on the literature gathered for this review.

For strip manufacturing, Fig. 3 presents sustainable material selection choices for the working electrode, reference electrode, and substrate. In addition to the nanomaterials used in electrodes, a screen-printed electrode consists of inks dispersed in solvents, substrates, and mesh. The inks are divided into two types: conductive and insulating inks.[214] The basis of conductive inks is conductive nanoparticles or fillers dispersed within a binder matrix, facilitating efficient electron tunneling to enhance the interaction among fillers and between fillers and

Table 5 Decision matrix regarding performance, sustainability, scalability, environmental toxicity, recyclability, and LCA data availability

Working electrode materials	Performance	Sustainability	Scalability	Environmental toxicity	Recyclability	LCA data availability
CNTs	Good	Fair	Good	Fair	Fair	Good
CNFs	Good	Fair	Good	Fair	Fair	Poor
Graphene	Good	Good	Good	Fair	Fair	Good
CDs	Good	Good	Good	Good	Good	Fair
MXenes	Good	Poor	Poor	Fair	Fair	Good
MNPs	Good	Poor	Good	Fair	Fair	Good

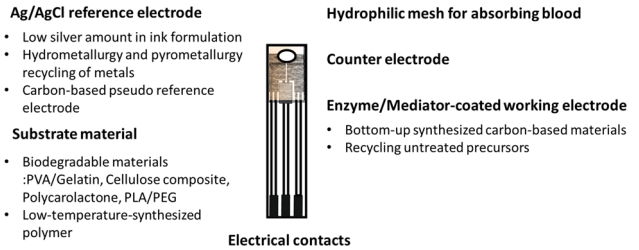

Fig. 3 Sustainable choices of materials used in disposable glucose strips, with a focus on substrate, reference, and working electrodes.

substrates. Conductive nanomaterials have already been discussed in this review. Commonly used binder materials include thermoplastic binders, such as ethyl cellulose (EC) and polyvinylidene fluoride (PVDF), as well as thermosetting binders, such as epoxy resins and acrylics. These materials are challenging to separate from inks and negatively impact biodegradable and recyclable possibilities. Therefore, materials derived from sustainable or natural resources, such as starches, sugars, lignin, and cellulose, can serve as alternatives.[210] Furthermore, while biodegradability and recyclability offer advantages, the environmental impacts of these processes may be considerable. Hence, conducting LCA of glucose sensors using proposed materials is recommended prior to mass production.

4. Future outlook

Sustainable manufacturing of test strips can significantly reduce the environmental impact of self-measurements by embracing circular economy principles. This approach involves designing strips to minimize material use and incorporating biodegradable or renewable materials. Integrating sustainable energy sources into production and selecting non-toxic, low-impact materials can greatly lower the environmental footprint of these commonly used disposables. Key efforts could include developing nanomaterials, using biobased or renewable materials, and promoting miniaturization.

In the design process, the main environmental benefits can be achieved through changes in the upper parts of the life cycle, *i.e.*, the raw material and production phases of the strips. Several studies have been carried out to develop the use of biobased or biodegradable materials in this field. A notable advancement in this area has been the development of fully transient electrochemical test strips. These strips utilize soluble polymer-based materials and non-toxic carbon-based conductive pastes, allowing them to maintain functionality during use and completely degrade within a week of disposal. The replacement of traditionally used strip materials with these substances may potentially result in lower climate and other environmental impacts. Recent sustainable strategies for sensor development have drawn attention, including the use of bacterial cellulose, MXene-based self-powered electrochemical sensors, and low-temperature polymeric sensors, as they are biocompatible, energy-efficient, and generate less waste during manufacturing. For example, bacterial cellulose has proven useful in biomedical applications,[215,216] flexible devices, and supercapacitors.[217] MXene-based self-powered electrochemical sensors have promise in addressing the limitations of electrochemical sensors that rely on external power sources, providing self-sufficiency and thereby reducing environmental impact.[218] The challenges associated with recent advances in nanosensor design include scalability, cost, stability, and difficulty in producing materials. To address these limitations, a scalable dip-coating method for producing biodegradable electronic textiles was reported for wearable biomonitoring.[219] Additionally, low-temperature-synthesized polymeric sensors have drawn attention due to their lower energy consumption and scalability.[220]

While such degradable strips offer an alternative to traditional non-degradable strips, thus potentially also decreasing the environmental impacts of the waste management processes, safety issues in the medical field often complicate their adoption for consumables. EU Regulation (2017/745/EU) outlines the responsibilities and requirements necessary to ensure the safe reuse of single-use medical devices, which, where national law permits, provides further possibilities to increase the sustainability of medical devices.[221,222]

Producing silver nanomaterials has higher environmental impacts than bulk silver due to their energy-intensive synthesis and greater resource use. However, the bulk production of silver contributes over 90% of the total life cycle. At the end-of-life stage, nano silver poses notable ecotoxicity risks as particles or ions can be released during disposal (landfill or incineration), with up to 50% potentially leaching out during use and small fractions entering air or water systems. While the global warming impacts remain low at disposal, the ecotoxic and long-term environmental effects are more significant for nano silver than for bulk materials.[173,223] Furthermore, the European

Commission highlighted that nano silver in waste can act as a persistent source of ionic silver contamination in soil and aquatic environments.[224]

Artificial intelligence (AI) holds immense promise for advancing the sustainable synthesis of nanomaterials.[225,226] By analyzing large datasets, AI and machine learning can optimize reaction conditions, select precursors, and fine-tune synthesis parameters, leading to more efficient, resource-conscious processes with reduced waste. AI also facilitates the design of novel nanomaterials and nanocomposites by predicting material behavior and exploring vast chemical spaces, accelerating the discovery of high-performing, sustainable materials. For example, AI can optimize the overall synthesis process by reducing waste and energy consumption. Moreover, machine learning can support sustainable development by enhancing Environmental Risk Assessments (ERA). However, the lack of clear guidelines and standards for the use of machine learning in ERA, particularly for nano- and smart materials, calls for strategic efforts.[227] Priorities include strengthening data foundations, methodologies, and addressing biases to prevent their integration into machine learning systems. Although AI models are developed by computer scientists, experimental scientists should be well-trained to use them to determine the adequacy of data sets and understand the AI outputs. Interdisciplinary collaboration among computer scientists and experimental scientists is essential to address challenges in AI and machine learning, such as dataset standardization and the validation of AI models by aligning with their methodologies and goals.

According to Hosseinian *et al.* (2025),[9] the environmental impact of diabetes management can be reduced by decreasing the amount of materials used in the strips. One of the major contributors to the carbon footprint of glucose management is the consumable parts, which include single-use test strips. Based on current practices, the only component typically recycled is the strip container, which is usually made from polyethylene. In total, the carbon footprint of the strips and their containers contributes approximately 33–48% of the overall carbon footprint of self-monitoring of glucose. This highlights how a better design of these components could lead to significant reductions in the environmental impact of glucose measurements. There have been some developments regarding the miniaturization of devices and consumables, aimed at reducing environmental impacts and waste generation, thereby improving the sustainability of the diabetes management process. The development of a flexible, TiO_2 nanofiber-modified carbon cloth electrode represents a promising step toward miniaturized glucose monitoring.[228] Its high sensitivity, durability, and compatibility with wearable formats make it a strong candidate for next-generation biosensors.

Finally, when commercializing the product, packaging must be a key consideration. Disposable diabetes devices generate significant amounts of plastic and other waste, yet the devices themselves may account for only 10% of the total weight and volume, with the rest attributed to packaging.[229] For continuous glucose monitoring devices, as shown in the results from Hosseinian *et al.* (2025),[9] the primary contributors to the carbon footprint are the instruction leaflet and plastic components. This may change in the future, as more medical products may only have electronic instructions instead of paper ones (2021/2226/EU).[230]

While this paper focuses primarily on sustainability aspects, techno-economic considerations are critical for future translation and large-scale deployment of the proposed sensing strips. In particular, scalability of the fabrication processes, selection of low-cost, manufacturable materials, and compatibility with existing roll-to-roll or batch manufacturing techniques will ultimately determine commercial viability.

5. Conclusions

Evaluating environmental performance solely through carbon metrics risks overlooking other critical areas of concern. A more comprehensive analysis is needed to capture the full spectrum of potential impacts. However, traditional LCA methods often fall short in accounting for nano-specific characteristics, such as unique surface reactivity, size-dependent toxicity, and transformation pathways in the environment, that can significantly influence impacts across the life cycle. In this context, the nanocircular economy offers a relevant framework for integrating these considerations into sustainable design and management of nanomaterials. However, methodological development in LCA (or more broadly, in environmental assessment) is needed to adequately capture these important aspects.

Beyond carbon emissions, other overlooked impacts, such as material waste and recycling limitations, also shape the environmental footprint of test strips. Overall, by minimizing the use of samples, materials, and other resources, these strips offer a more sustainable approach and align well with contemporary environmental demands. However, their large-scale deployment generates substantial waste annually, much of which is not currently recycled. Recycling in health technology remains limited, in part due to strict requirements related to patient safety and ethical considerations.

Many authors imply that using nanoparticles maximizes use efficiency, yet they rarely quantify real metal savings or holistic environmental burden. Studies typically omit the environmental costs of nanoparticle synthesis (energy use, chemical waste, toxicity), making the sustainability claim weak or incomplete. On the other hand, many novel nanomaterials have not yet been utilized in industrial-scale applications. Thus, LCA or estimating the energy demands of industrial-scale production for novel materials that are currently only synthesized in gram quantities remains a significant challenge.

The core focus here was on the working electrode, as it is the sensor's functioning heart and a key focus of material development, also from a performance perspective. In this review, we examined alternative nanomaterials for electrochemical (bio) sensing transducers with an emphasis on their environmental implications, focusing on carbon nanomaterials, MXenes, and MNPs. Sustainable nanomaterial synthesis requires tailored strategies for each material class. For CNTs, the sustainable synthesis demands optimizing process parameters and shifting to renewable precursors, with machine learning offering

powerful tools to reduce environmental impacts and to enable scalable production. The sustainability of graphene synthesis depends on minimizing toxic reagents and byproducts, adopting biomass-based precursors, and developing recycling methods for copper foil, as well as greener transfer techniques. For MXenes, reducing hazardous chemicals, lowering energy consumption, and advancing safer etching and exfoliation methods are key, as both synthesis routes and laboratory energy demands significantly impact the environment. MNPs call for green, bottom-up approaches that balance reduced toxicity and environmental burden with the preservation of their biomedical functionality. Overall, AI enables more sustainable nanomaterial synthesis by optimizing processes, reducing waste, and accelerating discovery through predictive modeling. To fully realize this potential, clear standards, robust data foundations, and transparent methodologies are needed, particularly for environmental risk assessments.

Besides the working electrode, other aspects need to be considered. Ag/AgCl remains the most common reference electrode in miniaturized devices, but greener alternatives with reduced silver content and biodegradable binders have been developed. The sustainable manufacturing of disposable sensors is increasingly emphasizing biodegradable substrates, green solvents, and natural binders, with the goal of replacing hazardous materials while maintaining printability and performance. Ultimately, selecting alternative materials and reimagining the life cycle of test strips could significantly reduce the environmental impact of personal healthcare technologies.

Conflicts of interest

There are no conflicts to declare.

Abbreviations

LOD	Limit of detection
CVD	Chemical vapor deposition
GWP	Global warming potential
CTAB	Cetyltrimethylammonium bromide
DMF	Dimethylformamide
NMP	*N*-Methyl-2-pyrrolidone
THF	Tetrahydrofuran
SDBS	Sodium dodecyl benzene sulfonate
SDS	Sodium dodecyl sulfate
CNTs	Carbon nanotubes
PET	Polyethyleneterephthalate
CNFs	Carbon nanofibers
CDs	Carbon dots
MNPs	Metal nanoparticles
PLA	Polylactic acid
PDMS	Polydimethylsiloxane
PU	Polyurethane
PVC	Polyvinyl chloride
Na-CMC	Sodium carboxymethyl cellulose
PVA	Polyvinyl alcohol
PLGA	Poly(lactic-*co*-glycolic acid)
PCL	Polycaprolactone
PLLA	Poly-L-lactic acid
PGS	Poly(glycerol sebacate)
PEDOT:PSS	Poly(3,4-ethylenedioxythiophene):polystyrene sulfonate
PLA/PEG	Polylactic acid/polyethylene glycol system
EC	Ethyl cellulose
PVDF	Polyvinylidene fluoride
AI	Artificial intelligence

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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