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Sustainable glucose meters: Circular economy insights from integrated life cycle assessment and material composition analysis

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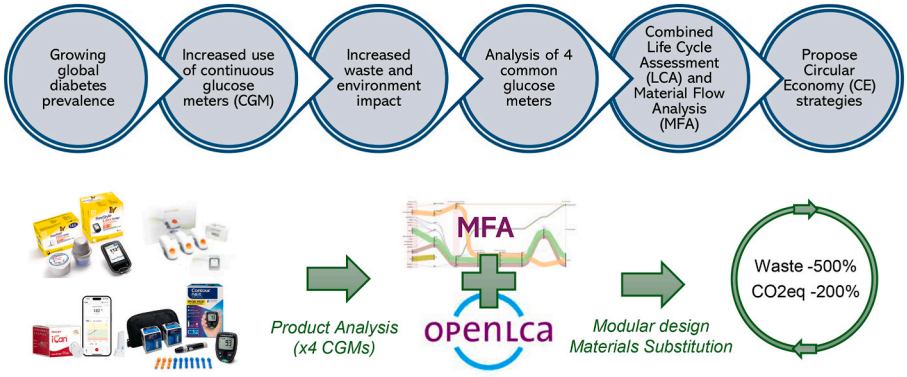
GRAPHICAL ABSTRACT



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ABSTRACT

Continuous glucose meters (CGMs) are increasingly used for diabetes management but raise environmental concerns due to short product lifetimes and materials-intensive designs. This study evaluates the potential of applying circular economy (CE) strategies to reduce the environmental impacts of CGMs. Our approach uses an integrated environmental assessment which combines life cycle assessment (LCA) with product-scale material composition analysis (MCA), informed by material flow analysis (MFA) principles.

Three commercially available CGMs were assessed and compared with a conventional finger-prick glucose meter as a baseline. Two CE scenarios were modelled: (i) a modular design, in which the applicator and transmitter were redesigned as reusable components with extended lifetimes while allowing single-use needle replacement, and (ii) material substitution, where polycarbonate components and packaging were replaced with lower-impact alternatives.

Across all case studies, the CE scenarios reduced combined product and packaging material use by 54–84% and climate change impacts by up to 66.5% relative to the extant (non-circular) baseline. The modular design

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scenario delivered the greatest environmental benefit by extending the functional lifespan of key components. Packaging and electronic components were thus identified as dominant environmental hotspots, indicating priorities for future redesign.

Overall, the results demonstrate that CE-oriented redesign can substantially improve the environmental sustainability of CGMs without compromising functionality and highlight the value of integrating material composition mapping with LCA to support sustainability-driven medical device design.

1. Introduction

1.1. Prevalence of diabetic in the UK and diabetic device waste

It is estimated that by the year 2030, one in ten adults in the UK will have diabetes unless substantial lifestyle changes are implemented (Iacobucci, 2021). The most recent data from the diabetes atlas estimates over 4.4 million people in the UK suffer from type 1 or type 2 diabetes, which is 7.4% of the adult population (International Diabetes Foundation, 2025). Worldwide, it is estimated that 589 million adults suffer with diabetes, with estimated grow to 853 million by 2050 (International Diabetes Foundation, 2025). With such a huge number of people with diabetes, diabetes has been declared a public health emergency (Iacobucci, 2021).

Diabetes technologies are crucial in preventing blood sugar spikes and long-term organ damage (Klonoff et al., 2020; Lopes and Sousa Lages, 2022). However, their increasing use has resulted in significant waste, estimated to reach 20.580 tons annually (Chowdhury et al., 2024; Petry et al., 2024). The issue prompted the 'Green Diabetes Summit' in 2021, highlighting the need for actionable strategies that prioritise circular strategies of reduction, reuse, recycling, and redesign of devices for diabetes care. In particular, the summit emphasized the need to reconsider design, particularly reducing material intensity and extending the device life for greater environmental benefit (Nguyen et al., 2022).

1.2. Glucose monitoring and sustainability

The conventional glucose meter requires a finger prick with disposable strips and needles, five to six times daily (Didyuk et al., 2021). A continuous glucose meter (CGM) offers clinical advantages and user convenience (Olczuk and Priefer, 2018). A CGM pack consists of packaging, manuals, a large applicator with an 'access needle', a transmitter, and a sensor with micro-needles that are continuously in contact with interstitial fluid. The CGM sensor is placed on the back of the arm or on the abdominal surface, and longevity varies from 7 to 180 days (Didyuk et al., 2021).

CGMs are typically difficult to recycle. Apart from cellulose-based packaging and manuals, the core parts are considered mixed-waste, comprising multi-component assemblies with needles, batteries, and electronics which require separation and decontamination (Martin-Cabezuelo et al., 2024; Didyuk et al., 2021). Furthermore, they lack straightforward end-of-life (EoL) pathways (Heinemann and Klonoff, 2022). As a result, the complete CGM package, including the large applicator, is typically disposed of, alongside the sensor, for incineration or landfill at EoL. Patient and stakeholder groups have highlighted their concern at the degree of waste associated with CGMs and requested improved sustainability and transparency on EoL. (Greener, 2023; Heinemann and Klonoff, 2022). The commercial response has been limited to date; in the US, Abbott has developed CGM collection schemes to support incineration for energy generation, while in the UK few options exist, the closest being Novo Nordisk collecting insulin pens for recycling of constituent polymers into park benches. (Greener, 2023). However, while these options improve upon landfill, their benefit is limited and fails to address the central challenge that CGMs are single-use devices (Kristensen and Mosgaard, 2020).

The seminal 'Green Surgery Report' proposed the CE as central to reducing the environmental impact of medical devices, placing an emphasis on replacing single-use medical devices with reusable alternatives (Bhutta et al., 2023). The 'circular economy' (CE) defines a set of principles aiming to maximise the utilized capacity of goods and turning goods at end-of-life into new resources (Basu et al., 2024). CE aims for narrowing, slowing, and closing of 'resource loops' (Guzzo et al., 2020; Hoveling et al., 2024). Narrowing the loop involves reducing material resource used, slowing the loop involves prolonging useful life, closing the loop concerns reusing resources at EoL in a manner which prioritises keeping them in the highest value state. Accordingly, a hierarchy of options exist; device reuse is the most favoured option, then repair/reprocessing, next remanufacturing (i.e. replacing some component parts) before finally recycling materials is considered the least desirable before waste through landfill or incineration (Guzzo et al., 2020; Hoveling et al., 2024).

Research quantifying the environmental burden of continuous glucose monitoring (CGM) spans device-level life-cycle assessments (LCA), empirical waste audits, and component-focused sustainability analyses. A recent cradle-to-grave comparative LCA found that under typical use, CGMs have increased carbon footprints compared to traditional finger prick monitors, with major contributing factors included plastic housings and paper instructions for use(Hosseinian et al., 2025). These findings were mirrored in an observational US study concerning diabetes devices, finding monthly waste of 1.2–1.4 kg per user, equivalent to 1–2 % of total household waste. Excessive packaging and limited recycling options were again cited as key factors(Petry et al., 2025; Tian et al., 2025). Complementing these LCAs, a mass-balance analysis of mainstream CGMs found that packaging, instructions and applicators dominate product waste mass (Petry et al., 2024). More focussed analysis has examined the contribution of batteries within single-use CGMs, highlighting the wider environmental impact beyond carbon equivalent emissions, including ecosystem toxicity and resource use (Avari et al., 2024; Chowdhury et al., 2024). Building on these works, an innovative approach was employed to integrate life-cycle assessment (LCA) with diffusion modelling to estimate CGM environmental impacts between 2025 and 2050 based on market trends. This work highlighted both the dominance of material extraction and manufacturing processes across the product life-cycle in carbon equivalent emissions, and that CGMs will dominate the wearable healthcare device market by 2025, making their environmental impact particularly important (Yang et al., 2026).

1.3. Evaluating circularity and environmental impact

CE has become an increasingly popular tool for addressing sustainability concerns and is analysed using range of approaches, including materials flow analysis (MFA) as demonstrated in previous studies (Amicarelli and Bux, 2022; Gonçalves et al., 2024; Lupton and Allwood, 2017; Na et al., 2024). Outcomes from MFA are often visualized using a Sankey diagram, which can readily show the composition and 'flows' of resource used, waste streams and linear and circular scenarios (Lupton and Allwood, 2017). However, aspects such as materials extraction, manufacturing process, transport and distribution, and EoL treatment can be overlooked by using MFA in isolation (Cilleruelo Palomero et al., 2024). These aspects are covered by more comprehensive impact assessments such as LCA (Samani, 2023). Accordingly, the outcomes of circularity assessments and LCA should be considered as complementary views on a particular environmental scenario, with neither providing a complete picture on its own (Baars et al., 2022; Samani, 2023). This

underlines the opportunities for developing methodologies which integrate approaches used in existing methods, notably LCA and MFA, to provide a more complete environmental evaluation, with particular virtue to identify opportunities for implementation of CE in medical devices (Baars et al., 2022; Cilleruelo Palomero et al., 2024; Ohms et al., 2024; Samani, 2023).

1.4. Research gap and aim of the study

The principal research gap is the absence of sustainability analyses for widely used CGM platforms that rigorously evaluate opportunities to implement CE principles by considering alternative design options (e.g. modular/reusable electronics, reusable applicators, longer wear intervals, rechargeable batteries) within the constraints of clinical practice. Furthermore, while existing studies highlight the significant environmental impact of CGMs, they employ either LCA or mass/waste analyses in isolation. However, there are no integrated environmental assessments of glucose monitoring technologies that capture both material composition and life cycle impacts to support circular design strategies for these critical devices.

This study aims to address this knowledge gap by developing an integrated assessment combining LCA with analysis of material composition (following principles of MFA) to assess resource use and environmental impacts of commercial glucose meters. Our hypothesis is that this approach will enable a detailed evaluation of the value of applying circular economy strategies to CGMs, including modular design and material substitution.

This work is important because CGMs are projected to become one of the most prevalent wearable healthcare technologies and based on current single-use models, would confer a huge environmental burden (Yang et al., 2026). There is a lack of understanding in how to effectively tackle this challenge. To the author's knowledge, this is the first medical device study to integrate LCA with analysis of material composition. This study therefore offers a novel framework for evaluating circular design opportunities in small medical devices, in particular CGMs.

2. Method

This study involved a breakdown of the glucose meters, followed by the identification of materials using Raman spectroscopy and energy-dispersive X-ray (EDX) analysis. The data are then used to conduct a LCA and MFA.

2.1. Stage 1: model selection and information

A range of three CGMs were selected for analysis in conjunction with a conventional 'finger-prick' meter in this study. The two main CGMs available for prescription on the UK NHS are the Dexcom One G6 (Dexcom Inc.) and Freestyle Libre 3 (Abbott Laboratories Limited), (Avari et al., 2023; Garg, 2023). The devices analysed in this study were selected because they represent market leading products typical of the device category, for which alternative manufacturers and models exist. Brands are identified for transparency and reproducibility. Their inclusion does not imply endorsement, recommendation, or preferential evaluation by the authors. These products are representative examples within a broader device category. The key characteristics and system parameters of the selected CGMs are summarized in Table 1.

These align with UK NICE recommendations for glucose monitoring (National Institute for Health and Care Excellence, 2022), and are representative of the main international market in stand-alone CGMs. Medtronic's Guardian series is also a market leader but is associated with closed-loop care (in which the CGM links to an insulin pump) and is therefore not considered here (Edward and Priefer, 2023). The Sinocare iCan i3 (Sinocare) is an emergent stand-alone CGM model, focusing on providing a lower-cost option to European and Chinese markets, thus a useful contrast to more established brands (Jendrike et al., 2025). In addition, the Contour Next (Ascensia Diabetes Care) is the mainstream 'traditional' finger-prick glucose meter (NHS, 2023). Henceforth, these selected models will be referred to as Dexcom One (DO), Sinocare iCan i3 (SC), Freestyle Libre 3 (FL), and Contour Next (CN). DO can be used up to 10 days, SC can be used for 15 days, while FL can be used for up to 14 days.

2.2. Stage 2: materials identification

The samples were labelled according to their brand. Each glucose meter underwent mechanical disassembly. Each part was labelled, weighed, and grouped based on the similarity of materials. Fig. 1a Depicts the disassembled CN, Fig. 1b Depicts the disassembled DO, Fig. 1c Depicts the disassembled SC, and Fig. 1d Depicts disassembled FL.

2.2.1. Sampling criteria

The sampling criteria were established by following three steps as follows.

1. ***Material distinctiveness:*** Disassembled components were initially grouped based on observable characteristics (i.e., texture, rigidity, transparency) to infer likely material classes. Some components had material-type labelling from the manufacturer and were therefore excluded from further Raman identification (labelled as 'specified' at Appendix B). Raman spectroscopy was then employed to determine the identity of unspecified materials. To optimise analytical resources, clearly similar materials were only analysed once across our range, for example Raman spectroscopy confirmed that the next CN device's external packaging was cellulose-based which was assumed to be consistent for the other products (DO, SC, and FL).
2. ***Weight-based priority:*** In alignment with established LCA practices, components contributing a higher percentage to the overall device mass were prioritized for analysis, as heavier materials tend to have a proportionally larger environmental impact. The weight percentage of examined parts is provided in Appendix B.
3. ***Sample size justification:***
   A total of twelve representative samples were selected from each of CN, DO, and SC. Due to its relatively low overall mass, only six distinct parts were identified and sampled from the FL.

2.2.2. Characterization: SEM, EDX, and Raman spectroscopy

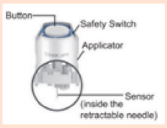
The plastics-based samples were analysed using SEM-EDX and Raman spectroscopy. Some soft plastics, such as low-density polyethylene, were challenging for SEM to image due to their low melting temperature. Therefore, some soft plastics only have Raman data. Meanwhile, the metallic-based samples only have EDX data, as EDX clearly reveals their metallic composition.

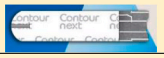
2.2.2.1. SEM-EDX. Materials identification was conducted using scanning electron microscopy NOVA NANOSEM combined with energy dispersive X-ray (EDX) (at the Department of Chemistry, University of Leeds) to identify the elemental composition of some parts of the glucose meter. For the EDX examination, 20 kV voltage was applied with a resolution of 122.6 eV, scanning time of 50 s, and magnification of 327-1143x. Elemental quantification was carried out using EDAX TEAM software and compared against the eZAF Smart Quant database.

Calibration of the EDAX EDS detector was performed annually to ensure accurate energy scaling and reliable peak identification. The calibration followed the manufacturer's recommended procedure and employed aluminium (Al) and copper (Cu) standards at an accelerating voltage of 20 kV. As EDAX systems use a standardless quantification method, no additional calibration for quantitative analysis was required.

2.2.2.2. Raman spectroscopy. Raman spectroscopy The XploRA PLUS Confocal Raman Microscope HORIBA Scientific USA (Department of

Table 1
Unit number per supply of a range of different brands of glucose meters.

	Parts	Number	Duration of use (Scenario A-Baseline)	Duration of use (Scenario B-Circular)
Dexcom One (DO)	Applicator 	1	10 days	App body 90 days App needle 10 days
	Sensor 	1	10 days	10 days
	Transmitter 	1	90 days	90 days
	Packaging	1	10 days	90 days
	Manual	1	10 days	90 days
	Parts	**Number**	**Duration of use (Scenario A-Baseline)**	**Duration of use (Scenario B-Circular)**
Sinocare iCan i3 (SC)	 Applicator	1	15 days	App body 90 days App needle 10 days
	Sensor 	1	15 days	10 days
	Transmitter 	1	15 days	90 days
	Packaging	1	15 days	90 days
	Manual	1	15 days	90 days
	Parts	**Number**	**Duration of use (Scenario A-Baseline)**	**Duration of use (Scenario B-Circular)**
Freestyle Libre 3 (FL)	Applicator 	1	14 days	App body 90 days App needle 10 days
	Sensor 	1	14 days	10 days
	Packaging	1	14 days	90 days
	Manual	1	14 days	90 days

	Parts	Number	Duration of use (Scenario A-Baseline)	Duration of use (Scenario B-Circular)
Contour Next (CN)	Lancet 	1	365 days	
	Meter 	1	365 days	
	Strip 	5	1 day	
	Needle 	5	1 day	
	Packaging	1	365 days	
	Manual	1	365 days	

Chemistry, University of Leeds) measures the frequency shift of the scattered light when interacting with vibrated molecules on the sample surface. The Raman spectrometer was calibrated prior to each measurement session in accordance with the standard operating protocol. A silicon (Si) wafer was used as the calibration reference to verify the characteristic peak position at ~520 cm^{-1} and ensure spectral accuracy. The obtained spectra were subsequently matched to the spectra library to identify the molecular structure.

The polymer specimens were cut according to size and shape and fitted into standard optical glass slides 25.4 x 76.2 × 1 mm (no brand specified CAT. NO.7101). The samples were run through red laser 785 nm wavelength (8.7 mW, 5.5-8.3 cm-1 resolution, and 50x objective magnification and were corrected for background fluorescence following the previously described procedures (Miller et al., 2022). Each sample was acquired in 20 s. The chosen spectra window range was 250 to 3500 cm^{-1}.

Post-processing steps were required because the recorded Raman spectrum will naturally have varying levels of signal noise and baseline fluctuations (Samuel et al., 2021). The post-processing was conducted using data analysis software (OriginPro v2024b). A smoothing filter (Savitzky-Golay, 2nd order polynomial) was applied using a 50 point window. The polynomial fitting allows continuous spectra intensity, which eases comparison at each wavenumber without missing points (Miller et al., 2022). Baseline correction was also performed (OriginPro v2024b), using manual baseline subtraction, the 2nd derivative zeroes method, and adjacent averaging smoothing. Each baseline correction used 20 points, using the spline line interpolation method. Since the spectra are sensitive to various experimental conditions, standard normal variate (SNV) normalization was carried out to allow comparable intensity variations of the spectra with intensity from 0 to 1 (Miller et al., 2022).

2.3. Stage 3: life cycle assessment (LCA)

Life cycle assessment (LCA) was carried out for the four brands of glucose meters: CN, DO, SC, and FL. For LCA, 18 midpoint environmental impacts were calculated. However, the primary focus is on climate change emissions, as measured by GWP100 and expressed in kg CO_2-eq. The study used the open LCA software 2024 with Ecoinvent 3.9.1 database, following ISO14040/14044 guidelines (Rizan et al., 2022).

2.3.1. Scenarios

The LCA was evaluated based on the provision of glucose monitoring for one patient-year. A range of scenarios were modelled to explore the effect of applying different Circular Economy principles to the CGMs. The resultant scenarios A, B, and C are described below.

2.3.1.1. Scenario A-baseline. Each glucose meter is used according to recommendations:

- DO: all parts are used for 10 days and then disposed of except the transmitter, which is kept for 90 days.
- SC: all parts are used and then disposed of every 15 days.
- FL: all parts are used and disposed of every 14 days.
- CN the applicator and lancet are reused for up to 1 year. Five samples are taken per day, according to NICE NG19 guidance, equating to 5 needles per day.

2.3.1.2. Scenario B-design changes. Design change scenarios were explored for the three CGMs (DO, SC, FL). A modular approach is proposed in which the lifespan of the transmitter and applicator body is extended to 90 days, such that only the applicator needle and sensor are replaced more frequently (as per the Baseline).

2.3.1.3. Scenario C-materials changes. Material changes were proposed for the applicator which forms the predominant mass in each CGM. While further material changes could be pursued, this approach provides an indicative outcome which can be compared to Scenario B.

The selection of materials was guided by current availability for manufacture in medical devices at scale, based on current industrial practices. This precludes some emergent alternative materials (e.g. bio-based polymers) but is intended to reflect what could be achieved at the current time. Recycled high-density polyethylene (HDPE) was chosen as a more sustainable alternative to polycarbonate (PC), given its widespread use in engineering applications and its higher recoverability rate (Yao et al., 2022; Förstner, Rulkens, and Salomons, 2019). Unlike PC, HDPE does not release potentially harmful substances such as bisphenol A (BPA), making it a better choice for a disposable device (Förstner, Rulkens, and Salomons, 2019). Additionally, HDPE can be biodegraded

Fig. 1. The four glucose monitor systems under analysis showing the main unit, packaging and a disassembly of the component parts in a) Contour Next Gen b) Dexcom One c) Sinocare i3 and d) FreeStyle Libre 3.

by certain microorganisms, offering a more environmentally friendly end-of-life option with reduced contaminant generation (Förstner, Rulkens, and Salomons, 2019). The choice to use HDPE is additionally justified by its presence in comparable components of existing continuous glucose monitoring systems, including the sensor, where it provides biocompatibility, manufacturability at scale, and compatibility with validated sterilization processes.

2.3.2. Goal and scope definition

2.3.2.1. Aim of LCA. The LCA aims to provide an impact comparison of different brands of CGMs, together with a self-monitoring and evaluate the impact of scenario changes.

2.3.2.2. Functional unit. The functional unit is defined as '*provision of glucose monitoring for one patient-year*', following ISO 14040/14044 guidelines and ensuring equivalence of the service delivered across the product alternatives. Representative use profiles for the CGMs are parameterised according to each device's Instructions for Use as follows: DO must be replaced every 10 days, SC for every 15 days, and FL requires replacement every 14 days, respectively. Meanwhile, the CN meter and lancet can be used for up to one year. The use defined for CN (as a finger-prick system) is 5 per day, consistent with UK NICE NG19 guidelines, thus 5 CN needles would be used per day.

2.3.2.3. System boundary. The LCA was a cradle-to-grave analysis encompassing the entire lifecycle, from raw material extraction and manufacturing, sterilization distribution, use, and EoL, as specified in Fig. 2. All parts, including packaging, were involved. The derived Bill of Materials and associated mass of each component, across each device, is specified in Appendix B.

2.3.2.4. Assumptions. The following assumptions are made: a 1% threshold is set for the single-unit product mass to include parts in the analysis. This follows ISO 14044, which allows the use of predefined cut-off criteria based on mass, energy, or environmental significance, provided they are transparently documented (International standard organization, 2006). Similarly, this threshold was mentioned in previous works (Gradin and Björklund, 2020; Tascione et al., 2024). Importantly, components with small mass but intensive energy use (i.e., semiconductor manufacturing and laser cutting needle) were also included regardless of mass to ensure completeness.

Integrated electronics are associated with high climate change emissions despite their low relative mass (Gargasson et al., 2025). The electronics sub-assemblies within CGMs are small, complex and low mass, making direct disassembly and composition of an electronics BOM, with associated component weights, challenging and beyond the scope of this study. Consequently, an aggregated model of the PCB assembly was derived using the overall mass of this assembly and the associated battery, consistent with other studies reported in the literature for inclusion of PCBs within wider LCAs (Kiemel et al., 2022; Zhang et al., 2024). The electronics assemblies were modelled using EcoInvent system-level aggregate models for manufacture and system-type (Gargasson et al., 2025) These values are presented as informed assumptions and are transparently reported to reflect this methodological limitation.

For DO and SC, the electronics are inside the transmitters. For CN, the electronics are inside the meter. Meanwhile, the FL does not have a transmitter, and its electronics are embedded in the sensor system. Other electronic parts are excluded from the analysis due to their small dimensions and relatively minor impact. An extra 10% of the mass is taken for raw materials required to account for manufacturing waste (Brändström and Eriksson, 2022).

For LCA, additional assumptions were made since more complex processes were considered. Transport is incorporated during the manufacturing process and distribution. Since the land transportation of raw materials to the manufacturing site is unknown, it is assumed to use a EURO 6 heavy goods vehicle (HGV) referred to as lorry in OpenLCA. Initially, the model utilized EURO 5. However, in the end, the Euro 6 was chosen based on the standard minimum vehicle emissions permitted in Europe and China (International council on clean transportation, 2017). Sensitivity analysis was conducted and revealed that the difference in climate change emissions between EURO 5 and 6 in the model was 0.05% of the total emissions, which is a very small percentage. As for water transportation, it used bulk carrier ships for dry goods.

During sterilization, it is assumed that ethylene oxide is used. Moreover, there may be associated climate change emissions related to the use stage (i.e., data transmission between the transmitter, Wi-Fi, the user's cell phone, and data storage), which was included in the analysis. However, the transmitter is not directly connected to Wi-Fi, but instead to a cell phone, and is only measured a few times a day, with an assumed average connection time of 1 h per day.

For transportation during distribution, it is also assumed to use a EURO 6 HGV. For distances less than 30 km, distribution to local pharmacies is assumed to be made using a light commercial vehicle. The same types of transport are used for all types of products, ensuring less variability and allowing a focus on emissions related to the products. At end-of-life disposal, all parts are assumed to be processed through high-temperature incineration.

2.3.2.5. Life cycle assessment of environmental impact. An impact assessment was carried out using the Ecoinvent database - ReCiPe 2016 v1.03, midpoint (H). This method evaluated 18 environmental impacts, including global warming, stratospheric ozone depletion, ionising radiation, ozone formation on human health, fine particulate matter formation, terrestrial acidification, eutrophication, ecotoxicity, human toxicity, land use, resource scarcity, and water consumption. The 18 midpoint impacts indicate direct chain impacts, while the endpoint impacts, including human health, ecosystem, and resource availability, estimate the final or long-term damage approach (Finnveden et al., 2009). This study scope focuses more on midpoint impacts rather than endpoint impacts because endpoint impacts have higher uncertainty and require more steps and assumptions to connect emission to the final

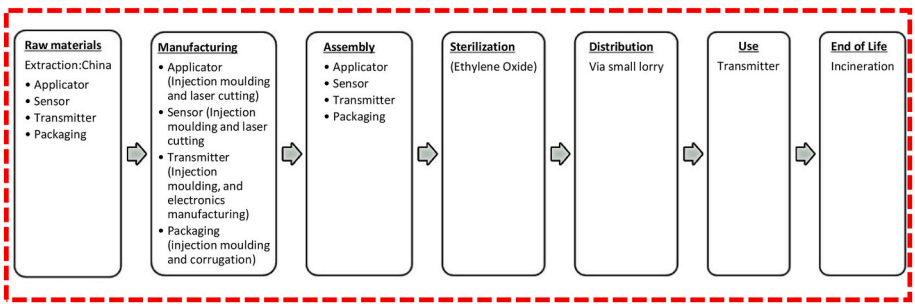


Fig. 2. System boundary of the Life Cycle Assessment and Material Flow Composition as applied to each glucose meter.

damage. Moreover, the results of this study aim to be practical, with an easy understanding for industry stakeholders, enabling direct implementation (Finnveden et al., 2009).

As a complement to the midpoint impact, three endpoint impacts are considered: (1) total impact on natural resources (USD, 2013) and (2) total impact on human health (DALYs). These impacts represent the key decision-relevant endpoints of resource scarcity and health burden.

Further analysis was carried out on climate change emissions, quantified as global warming potential over a 100-year time horizon (GWP100) and expressed in kg CO_2-eq, which were then combined with resource-use data from MFA to identify hotspots. The cumulative climate change emissions were the total contributions from raw materials extraction, manufacturing, packaging, sterilization, distribution, use, and end-of-life incineration. The inventory was developed by matching the materials or processes closest to the Ecoinvent. The distance for transportation was calculated using Pier2Pier online, as reported in a similar previous study (Rizan et al., 2022).

2.3.2.6. Sensitivity analysis. The core source of uncertainty is foreground inventory. Reverse engineering of the device to derive component composition and mass, including the identification of materials and the assignment of representative manufacturing processes, is a key source of uncertainty in this study. This sensitivity analysis is intended to test the robustness of comparative trends under plausible variations in key foreground assumptions, rather than to quantify statistical uncertainty or confidence intervals.

The sensitivity analysis on manufacturing waste rate and electricity mix partially addresses this uncertainty by testing the robustness of results to plausible variation in yield and energy intensity associated with assumed manufacturing processes.

Specifically, sensitivity analysis was conducted to examine:

(i) manufacturing waste rate (5%, 10% as baseline, and 20%)
(ii) end-of-life treatment assumptions with incineration as baseline, compared to landfill
(iii) electricity mix during manufacturing (CN/ROW vs. RER), and
(iv) transportation distance (+20%).

These parameters were selected based on their relevance to device manufacturing, data uncertainty, and prior LCA literature on disposable and reusable medical devices. Results are presented across all midpoint impact categories to ensure consistency and robustness of conclusions.

2.4. Material composition analysis (MCA)

In this study, material composition analysis (MCA) is inspired by material flow analysis (MFA). The principles were applied at the product scale to support the interpretation of the life cycle assessment (LCA) results. The analysis is static and aligned with the LCA life-cycle inventory (LCI), and therefore does not aim to represent a closed system, dynamic material stocks, accumulation, or recycling loops as typically addressed in meso- or macro-scale MFA.

Material quantities were derived directly from the LCI and allocated to individual life-cycle stages (material production, manufacturing, use, and end-of-life). The resulting Sankey diagrams visualize the distribution and relative magnitude of material inputs handled at each life-cycle stage, rather than net input–output mass balances or system-level material flows. Consequently, numerical values shown for each stage represent cumulative material throughput, not mass conservation or circularity metrics.

The purpose of this analysis is to improve transparency of product-level material composition and throughput, and to complement the LCA by facilitating interpretation of material-related environmental impacts, particularly where material mass does not directly correlate with environmental burden due to energy-intensive manufacturing or transport processes.

The analysis quantifies material inputs associated with provision of glucose monitoring for one patient year, consistent with the LCA system boundary, and allocates these quantities across all life-cycle stages, including (1) raw materials, (2) manufacturing, (3) assembly, (4) sterilization, (5) distribution, (6) use, (7) end of life.

The breakdown of materials and MCA data input can be accessed in the digital supplementary. For CN the meter, lancet, and packaging can be used for up to 365 days, while its strip and needle are single-use and require five units per day. Similar steps are implemented to determine the number of CGM components required to meet this lifespan.

To account for manufacturing losses, an additional 10% of the original material mass is included at the raw material extraction stage (Brändström and Eriksson, 2022). Materials are categorized into product components and packaging components to distinguish between functionally essential elements and those that may be minimized or redesigned.

The MCA was used to examine the same CE scenarios framework described in Section 2.3.1. However, as the analysis focuses on total material mass and throughput rather than material-specific substitution effects, only Scenario A (baseline) and Scenario B (design changes) are considered in this analysis.

2.5. Combined analysis

LCA and MFA are often reported separately in the literature (Gonçalves et al., 2024; Hunfeld et al., 2023; Zhang et al., 2024). In this study, both approaches are combined to demonstrate that higher material mass does not necessarily correspond to higher environmental impact. The results of the combined LCA and MFA are visualized using a modified Sankey diagram to provide a comprehensive view of both environmental impacts and material flows across the product life cycle. Fig. 7 provides the method flowchart to integrate environmental evaluation combining LCA and MCA.

3. Results

This paper carried out material identification, life cycle assessment (LCA), and material flow analysis (MFA). However, the particular focus for results is on the LCA and MFA. We first present the LCA results, which the MFA subsequently follows.

3.1. Materials identification

It was possible to identify all materials successfully. The results of this study provide material identification results obtained by Raman and EDX, which were subsequently used to inform LCA and MFA. The materials identification is provided in Appendix B, and the material

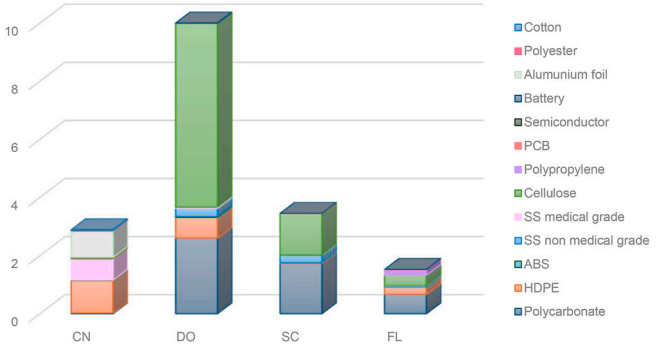


Fig. 3. Weight material composition of each glucose meter in kg, defined as provision of glucose monitoring for one patient year. CN = Contour Next, DO = Dexcom One, SC = Sinocare, FL = Freestyle Libre.

distribution is visualized in Fig. 3.

Fig. 3 illustrates the materials used for different range of brands have similarities in terms of materials used. For CGMs (DO, SC, FL) the most used materials are cellulose for construction of packaging. Polycarbonate is another predominant material of CGMs which construct applicator and sensor body. For CN, the predominant materials used in some parts (i.e. aluminium foil for strip packaging, SS medical grade and HDPE for needle and its holder.

3.2. Life cycle assessment (LCA)

Fig. 4a provides the non-normalized 18-point mid-environmental impacts, which have different units. According to ISO 2006b, normalization and weighting are optional to facilitate the comparison of impacts. It shows that SC SU has the highest terrestrial ecotoxicity potential (TETP), followed by DO SU in second place. However, in other environmental assessment aspects such as non-carcinogenic human toxicity potential (HTP nc), global warming potential (GWP 100), and non-renewable fossil fuel potential (FFP), DO SU dominates among all other brands and scenarios.

Fig. 4b1 shows the endpoint environmental impact for total impact to natural resources (USD, 2013), while Fig. 4b2 also shows the endpoint in total impact on human health (DALYs), while 4b3 shows total impact on ecosystem quality. From the impact of natural resources, DO SU has the highest impact (4.63 USD, 2013), followed by FL SU (4.54 USD, 2013), and SC SU (3.33 USD, 2013). When shifted to RU, the impacts decreased to 1.67 USD 2013 for DO RU, 1.54 USD 2013 for FL RU, and 1.12 USD 2013 for SC RU.

Similarly, in terms of total impact on human health, as shown in Fig. 4d, DO SU also dominates (0.0002 DALYs), followed by SC SU

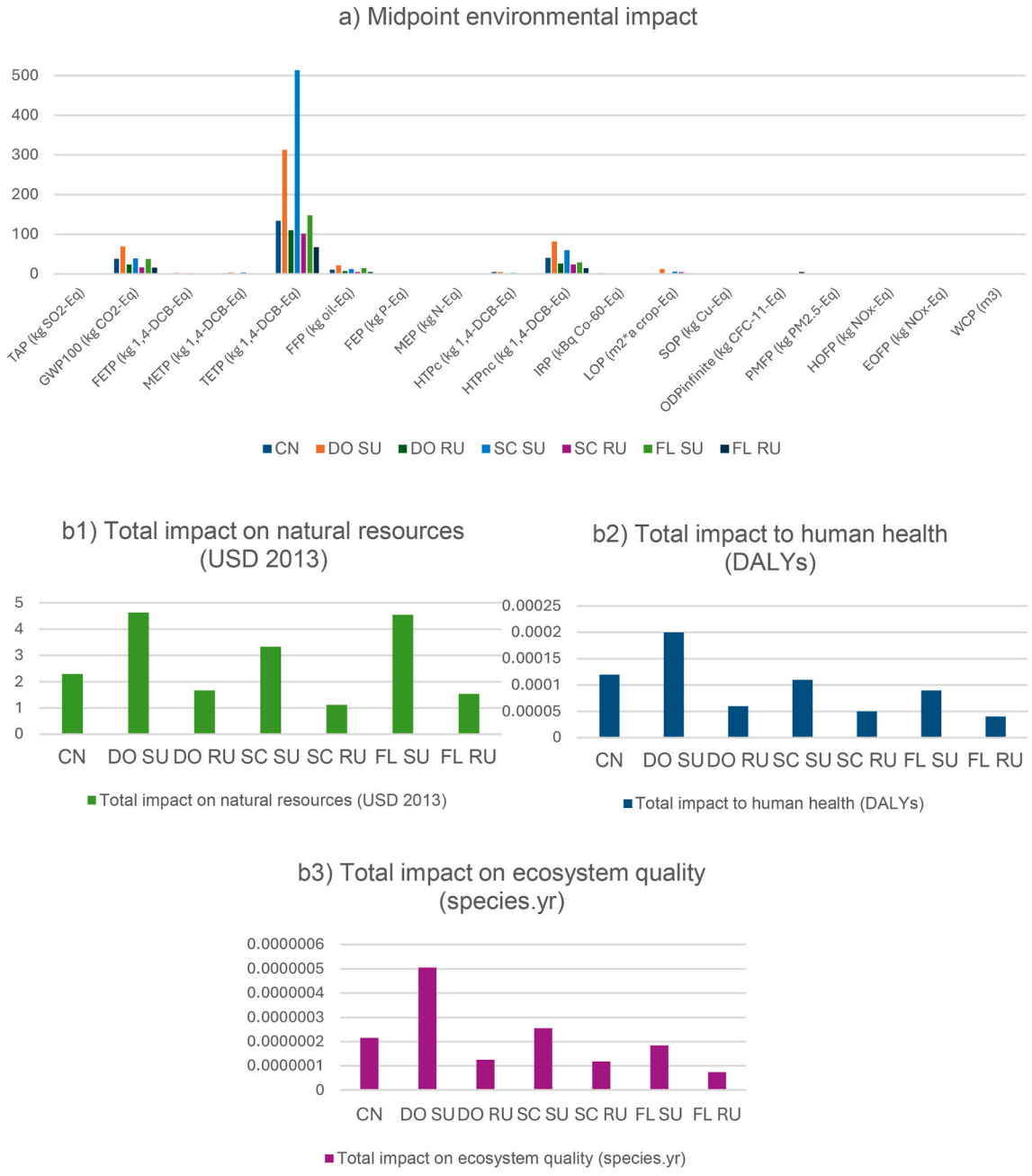


Fig. 4. Summary of environmental impact for the glucose meters, showing a) 18 midpoint environmental impact, b) endpoint impacts, defined as the provision of glucose monitoring for one patient year. CN = Contour Next, DO = Dexcom One, SC = Sinocare, FL = Freestyle Libre.

(0.00011 DALYs), and FL SU (0.00009 DALYs. When shifted to RU, a decrease was also consistently observed with DO RU (0.00006 DALYs), SC RU (0.000005 DALYs), and FL RU (0.00004 DALYs).

In terms of broader environmental impacts, both midpoint and endpoint results show that toxicity-related categories, terrestrial ecotoxicity (TETP) and human toxicity non-carcinogenic (HTPnc) are more dominant than the other impact categories. For the DO-SU and FL-SU CGMs, the main contributor to TETP is the polymer body of the applicator, followed by metallic needle production. HTPnc is primarily driven by carton-board packaging in DO-SU, whereas in FL-SU it is dominated by polycarbonate production used in the applicator.

Endpoint results show a similar pattern: total human-health impact is dominated by packaging followed by the applicator polymer body in DO-SU, and solely by the applicator polymer body in FL-SU. Total natural-resource use is also predominantly driven by the polymers used in the applicator.

For the SC-SU device, the transmitter, which contains electronic components, is the main contributor to TETP, HTPnc, and total human-health impacts. Similar to FL SU, total natural-resource use in SC-SU configurations is dominated by the injection-moulded polymers in the applicator.

Fig. 5a illustrates the distribution of climate change emissions across all life stages, including raw materials, manufacturing, sterilization, distribution, use, and end-of-life. For all types of glucose meters, climate change emissions are predominantly released during raw materials extraction and manufacturing.

Fig. 5b compares the climate change emissions which occur due to transport, product and packaging. Product and packaging account for

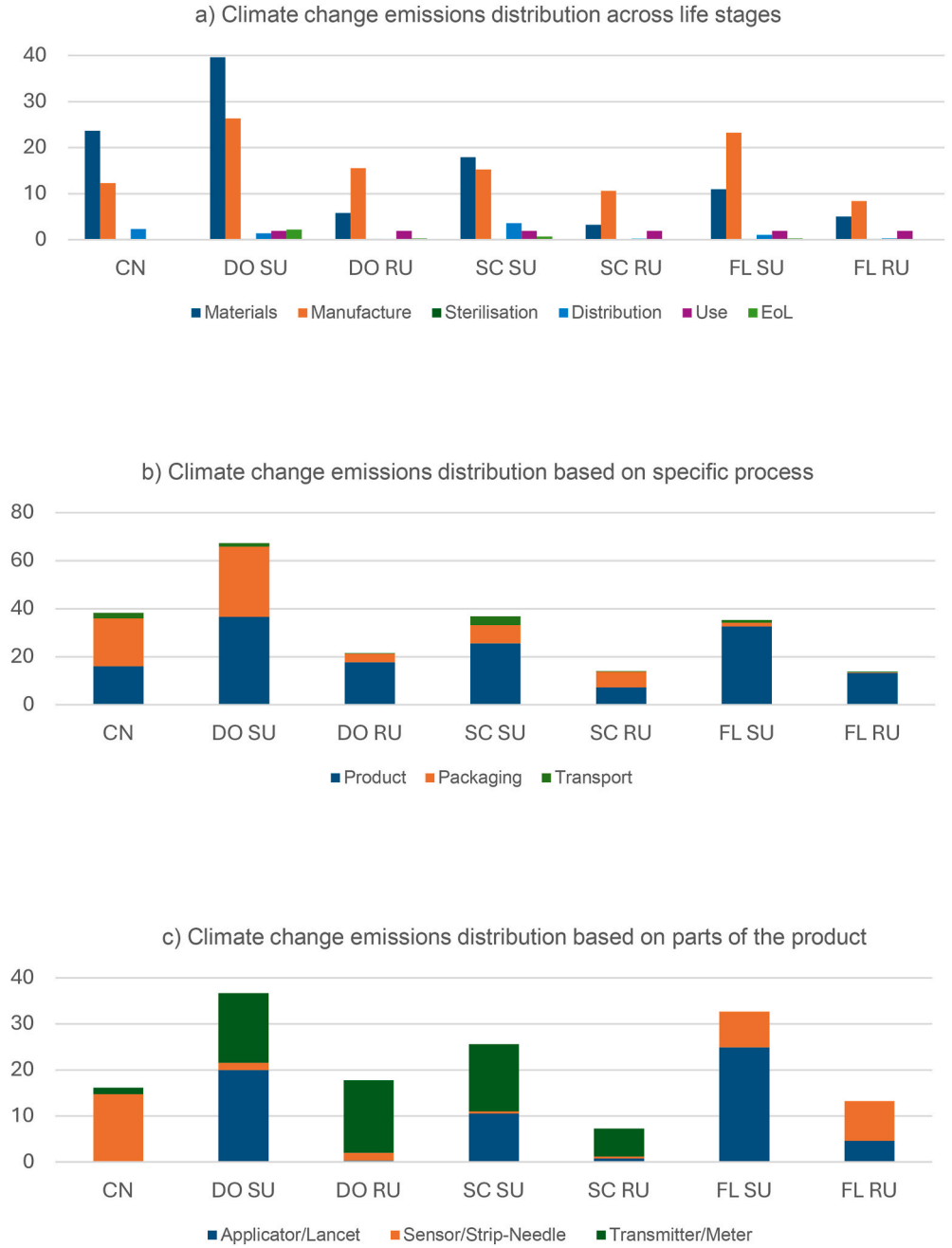


Fig. 5. Summary of environmental impact for the glucose meters showing a) the climate change emissions distribution (expressed in Kg CO2-eq) in b) different life-cycle stages, c) transport vs product d) component parts
CN = Contour Next, DO = Dexcom One, SC = Sinocare, FL = Freestyle Libre; SU=Single use (Scenario A), RU=Reusable (Scenario B).

the majority of climate change emissions (82-92% of total impact), while transportation contributes only ca. 0.8-10% of total impact.

Fig. 5c illustrates the climate change emissions distribution in component parts within the product (applicator/lancet, sensor/strip-needle, transmitter/meter). Applicator of CGM is an analogue of the lancet from the finger-prick system. While the sensor of the CGM is an analogue of the strip and needle of the finger-prick system. The transmitter of the CGM is analogous to the meter of the finger-prick system. The climate change result also indicate that the hotspot for CN originates from the strip needle (91%). For DO and SC, the predominant climate change impact comes from the applicator (54% for DO, and 41% for SC) and transmitter (41% for DO, and 57% for SC). The predominant climate change emissions for FL also originate from the applicator (76% followed by the sensor (47%), as it does not incorporate a transmitter. If we look further, the electronics (including the battery, PCB, and semiconductor) make the largest contribution to the transmitter and sensor parts. Semiconductor accounts for the largest share of the total climate change emissions, contributing between 19.5% and 37% across all systems.

The overall climate change emissions shown in Fig. 5b indicate that DO and SC emissions are higher (71.6 Kg CO_2-eq for DO, 39.7 Kg CO_2-eq for SC compared to the finger-prick system (38.5 Kg CO_2-eq for CN), attributed to the short lifespan of these parts. FL results in climate change emissions of 37.7 Kg CO_2-eq, which is slightly lower than CN. When Scenario B was applied (Fig. 5b), substantial reductions in climate change emissions were observed for all meters: DO (51.5% reduction), SC (71% reduction), and FL (59% reduction). Furthermore, 18 midpoint environmental impact results are provided in Appendix E, and their implications will be further discussed in the discussion section.

A sensitivity analysis was conducted to assess the influence of key modelling assumptions, including (i) manufacturing waste rate, (ii) end-of-life treatment, (iii) electricity mix during manufacturing, and (iv) transportation distance. The corresponding results are presented in Table E.1.2 in the appendix. The implication of the sensitivity analysis is discussed in Section 4.4.

3.3. Materials composition analysis (MCA)

The materials composition analysis (MCA) quantified the resources used and waste for provision of glucose monitoring for one patient year. Table 2 summarizes the material composition and packaging requirements for each glucose monitoring system under the defined scenarios, expressed per patient-year functional unit. The results are as follows.

The MFA indicates that for CN, the resource hotspots include 1.12 kg of HDPE from needle holder, 0.9 kg elastomer-titanium dioxide from the packaging strip, and 0.74 kg medical-grade stainless steel (SS316) from needle. In contrast, the hotspot for all single use CGMs does not originate from the sensor but rather from the applicator's body (polycarbonate, HDPE) and packaging (cellulose, HDPE). The DO utilizes 9.73 kg of cellulose, 3.21 kg of polycarbonate, and 0.88 kg of HDPE. Similarly, SC utilizes 1.47 kg of cellulose, 1.99 kg of polycarbonate. FL utilizes 0.41 kg of cellulose, 0.32 kg of HDPE, 0.72 kg of polycarbonate, and 0.23 kg of polypropylene.

The MFA show that Scenario A for DO (Fig. 6b) uses the most virgin materials and generates the most waste, followed by SC (Fig. 6c) and CN (Fig. 6a). However, the virgin materials and magnitude of waste for SC (total 3.5 Kg) and CN (3.66 Kg) are similar, indicating that SC has comparable resource usage to a 'traditional' glucose meter. In Scenario B, the resources used can be reduced 83% for DO, 79% for SC, and 54% for FL.

3.4. Integrated environmental evaluation combining MCA and LCA approaches

The outputs from the LCA (Section 3.2) and MCA (Section 3.3) were combined to provide an integrated environmental evaluation combining MCA and LCA approaches. The different scenarios were visualized using a series of modified Sankey diagrams (Fig. 6a–d) which indicates the resource use across the life-cycle, from materials to manufacture, sterilization, and end of life. The material flows are colour-coded according to material type, allowing the constituent resources to be tracked. Climate change emissions expressed in CO_2-eq are then collated and shown as an aggregate for each lifecycle stage.

Fig. 6a–d indicate combined materials flow with carbon data from LCA visualized in the red bars. Fig. 6a indicates the results for CN, representing current practice for a traditional glucose meter. Fig. 6b shows outcomes for DO, comparing Scenario A (baseline - current practice) with Scenario B (modular design changes). Fig. 6c indicates the results for outcomes for SC, comparing Scenario A (baseline - current practice) with Scenario B (modular design changes). Fig. 6d indicates the results for outcomes for FL, comparing Scenario A (baseline - current practice) with Scenario B (modular design changes).

The aggregated climate change emissions in Fig. 5a reveal the dominance of raw materials and manufacturing processes for all Scenarios. In comparison to Scenario A (Baseline), Scenario B reduced emission of DO from 71.67 to 23.9 kg CO_2-eq (66.5% reduction). For SC, Scenario B reduced the emission from 39.67 to 16.20 kg CO_2-eq (59% reduction) and FL from 37.72 kg to 16.06 kg CO_2 eq. (57.4% reduction). All the Scenario B emissions for all of CGMs brands are lower than that of CN (39.06 kg CO_2-eq).

Table 2
Summary of resource used for four different brands of glucose meters for each scenario.

Brand	Product (Kg)	Packaging (Kg)	% Reduction from Scenario A to B
CN	1.12 kg HDPE 0.74 kg SS Total: 1.86 kg	0.9 kg cellulose 0.9 kg elastomer titanium packaging strip Total: 1.8 kg	
DO: Scenario A	3.21 kg polycarbonate 0.88 kg HDPE Total: 4.09 kg	9.73 kg cellulose	84%
DO: Scenario B	0.56 kg polycarbonate 0.1 kg HDPE Total: 0.66 kg	1.58 kg cellulose	
SC: Scenario A	1.77 kg polycarbonate 0.27 kg of SS non-medical grade Total: 2.04 kg	1.47 kg cellulose	79%
SC: Scenario B	0.4 kg polycarbonate 0.05 kg of SS non-medical grade Total: 0.45 kg	0.29 kg cellulose	
FL: Scenario A	0.29 kg HDPE 0.67 kg polycarbonate 0.21 kg polypropylene Total: 1.17 kg	0.38 kg cellulose	54%
FL: Scenario B	0.06 kg HDPE 0.04 polypropylene 0.13 kg polycarbonate Total 0.23 kg	0.08 kg cellulose	

4. Discussion

This section discusses the key findings from the combined Life Cycle Assessment (LCA) and Material Composition Analysis (MCA). It examines the disconnection between material mass and carbon impact,

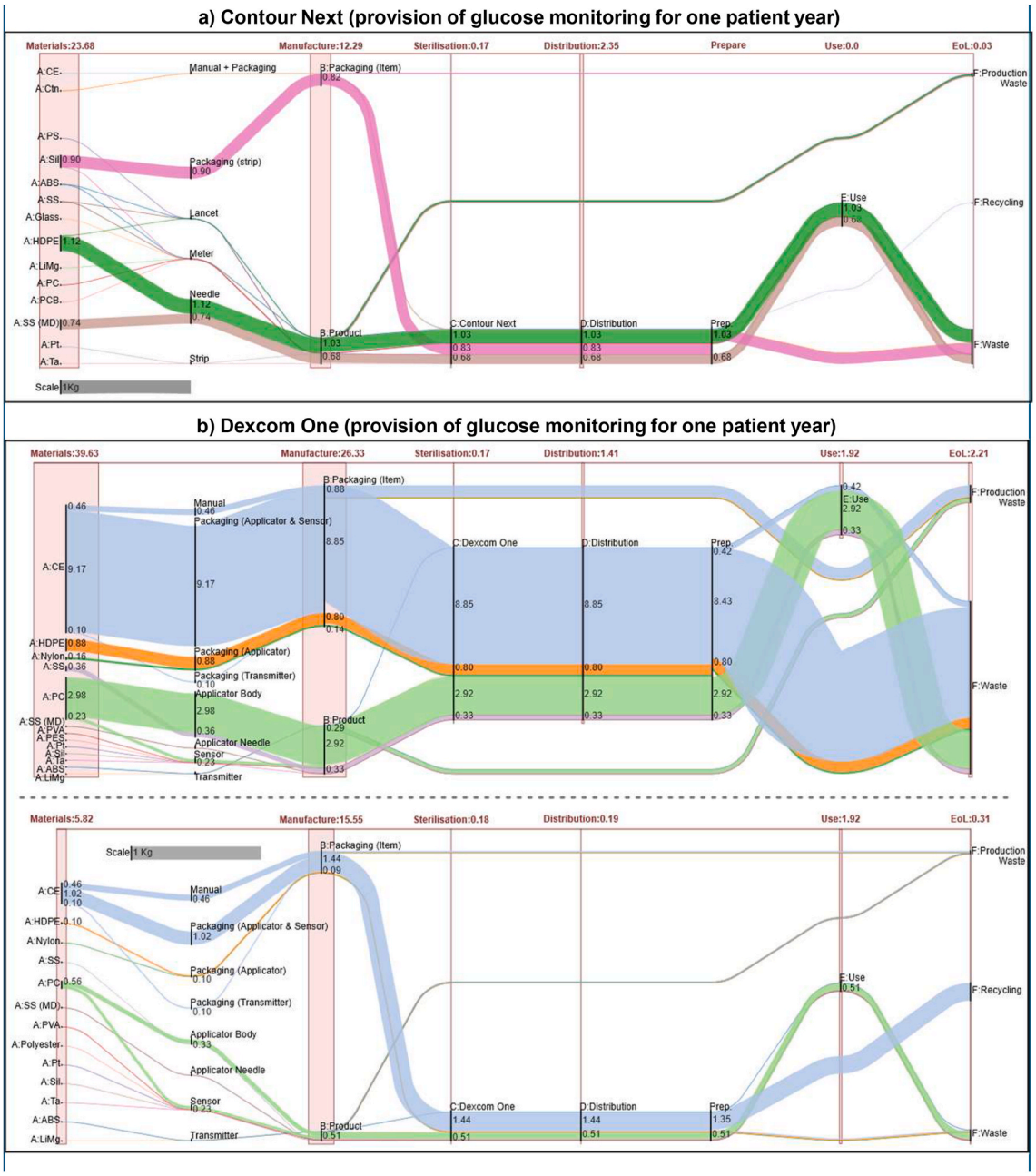


Fig. 6. A modified Sankey diagram showing Material Composition Analysis and Carbon Equivalent emissions (kg CO2-eq)for each major life-cycle stage of a) Contour Next b) Dexcom One Baseline Scenario (upper) and Circular Scenario (lower).
Material Composition Analysis is shown as flows running from left to right, coloured according to material type (Units Kg) per provision of glucose monitoring for one patient year. Carbon equivalent emissions (expressed in kgCO2-eq) are shown as light-red bars, the width of each denotes the magnitude of emissions at that life-cycle stage (kgCO2-eq). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

identifies key contributors to the environmental burden, and explores the implications of material choices, manufacturing methods, and design strategies for sustainable glucose meter development.

4.1. Insights from integrated environmental evaluation combining MCA and LCA approaches

The combined Sankey diagram (Fig. 6a–d) indicates that the relationship between material mass and the associated environmental impact is not always intuitive when comparing scenarios. In several instances, the diagrams highlight the disconnection between material mass and carbon emission. For example, although FL has the lowest mass (0.67 kg) among the products studied (CN 3.67 kg; DO 13.82 kg, SC 3.51 kg), the carbon emission of FL is comparable to that of SC (37.7 kg CO_2-eq compared to 39.7 kg CO_2-eq, respectively). When processes such as sterilization, transport, and incineration are excluded and focus solely on product parts, the emission of FL is slightly higher than that of SC (34.26 kg CO_2-eq compared to 33.25 kg CO_2-eq).

The discrepancy is likely influenced by factors such as the distance between raw materials extraction sites and manufacturing facilities. In the case of SC, the life cycle modelling assumes that both material sourcing and manufacturing occur in China, thereby reducing transport-related emissions. Another notable case is semiconductor components: despite their small size, they contribute disproportionately to as much as

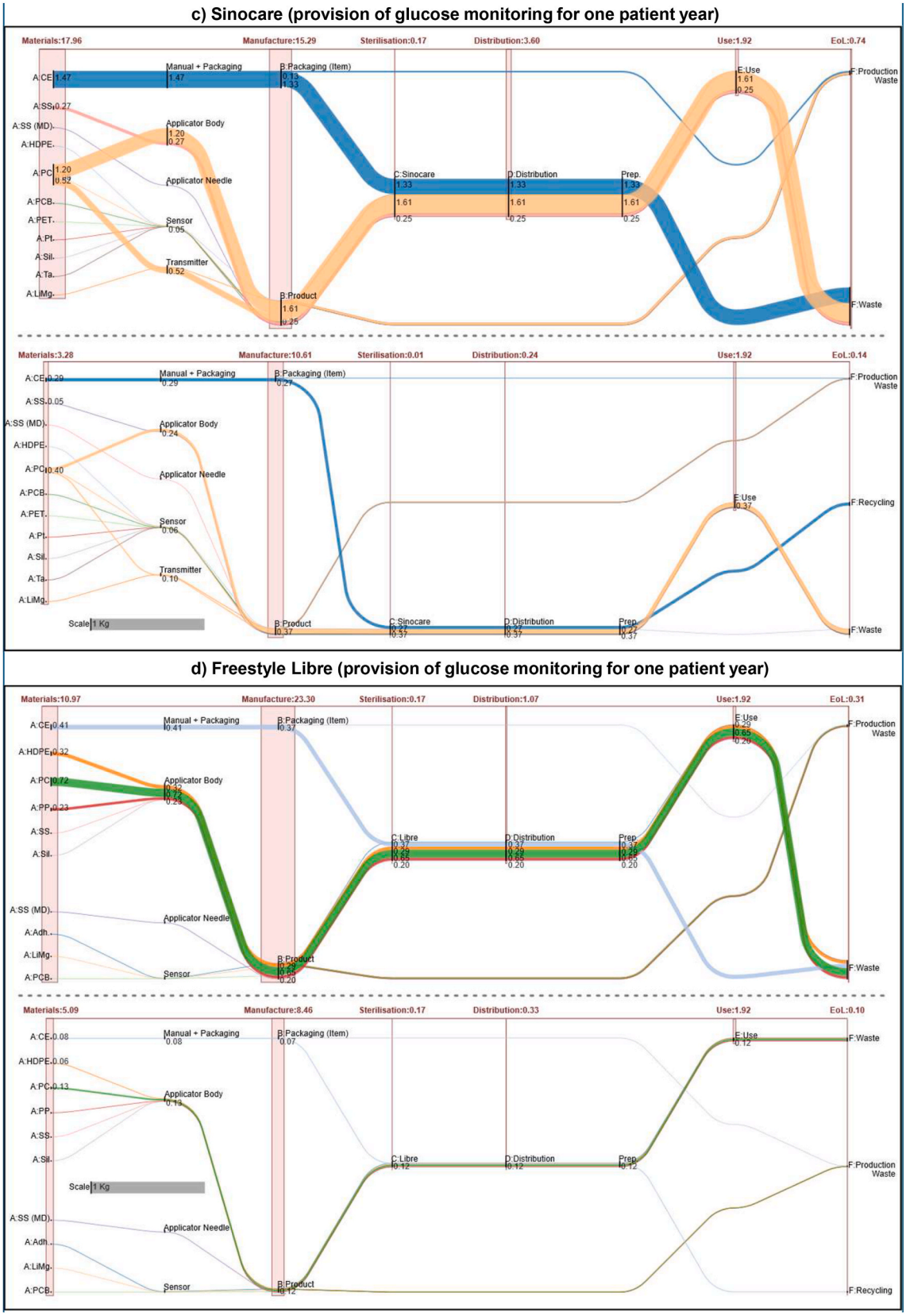


Fig. 6. (*continued*).

14 kg CO_2-eq due to energy-intensive manufacturing processes. These examples emphasise the fact that material flow alone is not a reliable environmental indicator. Variables such as extraction site location, transport distances, and manufacturing energy demands significantly affect environmental outcomes.

All these results highlight the importance of extending the applicator

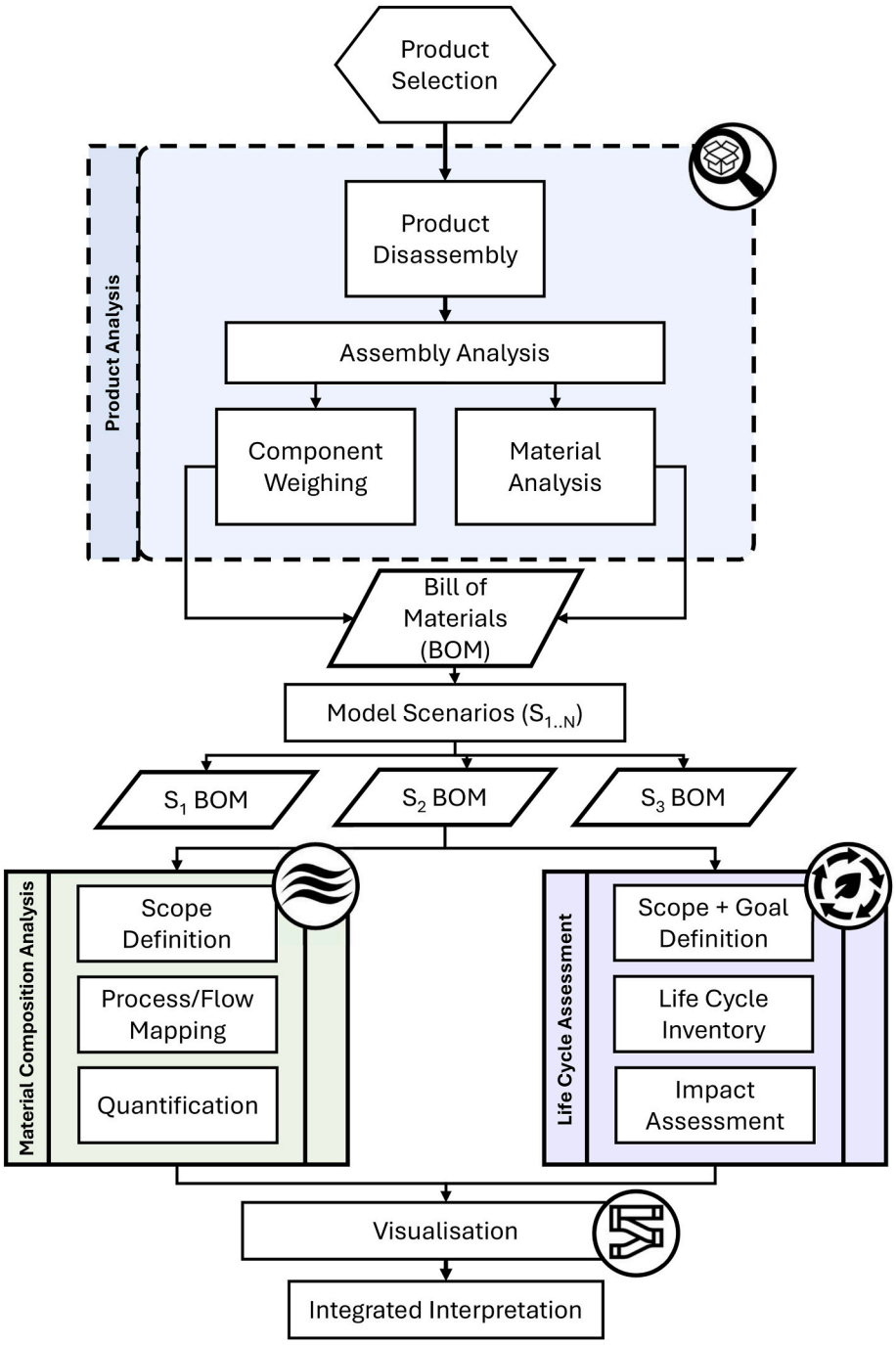


Fig. 7. A summary of the methodological framework for the integrated environmental evaluation used in this study which combines LCA and Material Composition Analysis (following principles of MFA).

body's lifespan and reducing packaging, as suggested in this study.

4.2. Materials and manufacturing method selection

Material selection and manufacturing processes play critical roles in determining the overall environmental footprint of glucose meters. Fig. 5a shows the distribution of glucose meters climate change emissions across life cycle stages, highlighting raw materials extraction and manufacturing as primary contributors.

For CGMs, the predominant material is Polycarbonate (PC), which is a common engineering plastic chosen for its versatility and excellent properties, such as transparency and thermal stability (Fukuoka et al., 2019). However, 99% of PC is synthesised indirectly from petrol-derived sources based on bisphenol A PC (BPA PC) (Zhou et al., 2023), which is environmentally toxic and can easily leach into the ecosystem during storage or landfill disposal (Contreras-Zarazúa et al., 2017). BPA has been detected in the bloodstream of mothers and infants more than any other chemical coming from medical devices (Czuba, 2014).

Life cycle assessment suggests that recycled PC can provide significant raw material resources to lower the impact of pollution (i.e. BPA leaching) (Zhou et al., 2023). Moreover, LCA demonstrated that recycling 1 ton of PC could potentially mitigate 4500 tons of climate change-related emissions annually. Recycled HDPE was chosen as an accessible alternative material (Scenario C) compared to the baseline (Scenario A) for the applicator body. It needs to be acknowledged that polyethylene also has a concerning impact on photodegradation when it

ends up in a landfill and exposed to the sun, leaking additives to the landfill, and microplastics swallowed by marine organisms (Yao et al., 2022). However, HDPE has relatively high recyclability and is hence chosen as a comparison material for the LCA. Recycled HDPE exhibits similar mechanical properties to PC, with no BPA risk. However, HDPE can be moisture permeable, making it unsuitable for housing sensitive electronics such as sensors and transmitters (Jaime et al., 2022).

Biopolymers (e.g., bio-PE, bio-PET, bio-PA) offer more sustainable alternatives but face challenges related to resource availability, cost, mechanical properties, thermal stability, biodegradation rates, and unfamiliarity with manufacturing processes (Negrete-Bolagay and Guerrero, 2024). Additionally, biopolymers intended for skin-contact applications must meet ISO 10993 standards for biocompatibility, and not all are available in medical-grade formats (Sastri, 2014).

In the case of CN, the predominant materials include needles and test strips, both of which are classified as infectious waste and cannot be reused or recycled. Although the medical-grade stainless steel used for needles is recyclable, its classification as infectious waste increases the risk of cross-contamination. Furthermore, biodegradable strips can be a way to reduce the waste that ends up in landfills.

In terms of alternative manufacturing processes, injection moulding and laser cutting appear to be the primary options for polymer moulding and needle production. Despite the high energy consumption, laser cutting offers a higher output, and its precision results in less material waste compared to more conventional machining methods, such as stamping or micro-machining.

4.3. Design changes

In addition to material and process choices, product design substantially influences environmental performance. Design strategies aligned with the circular economy, such as modularity, disassembly, lightweight, and reparability, can help mitigate impacts (Sgambaro et al., 2025).

The applicator and packaging represent major climate change emissions. Redesigning the applicator to support needle replacement and extended reuse, as proposed in Scenario B, aligns with modularity principles. However, current applicator designs are composed of mixed polymers, hindering recyclability, and often require tools for disassembly. Labelling is inconsistent, further complicating waste sorting.

Fig. 5b illustrates climate change emissions distributed from product and packaging vs. transport. The results confirmed that most emission stem from packaging and products, while transport contributes minimally. It was also confirmed in Fig. 5a that sterilization, use and end of life also contribute minimally. Notably, Fig. 5b shows that DO SU and CN exhibit climate change emissions from packaging that are nearly equal to those of the product itself, indicating opportunities to improve environmental impact by optimising packaging design and material reduction.

For the CN, recycling the needle is feasible with automated separation technology capable of detaching the stainless-steel needle from its HDPE holder. Even then, dealing with infectious waste remains a critical barrier. The more detailed design guidance is part of the ReMed design output (Circular Economy for Small Medical Devices | Research | ReMed.).

4.4. Assessment of 18 midpoint environmental impact

Fig. 4a indicates that DO SU dominates in 12 of 18 categories, including global warming potential/climate change, non-carcinogenic human toxicity potential, and non-renewable fossil fuel potential. This is attributed to its extensive packaging, large applicator body, and short usage cycle (10 days). SC SU leads in terms of the highest terrestrial ecotoxicity potential, possibly attributed to single-use (15 days) embedded electronics in the transmitter. While the other impacts of FL SU are relatively lower than those of other glucose meters, it has the highest impact on water consumption, possibly due to the specific use of materials or manufacturing process, such as polypropylene. The material flow analysis, supported by the midpoint assessment, confirms that Scenario B (modular design) effectively reduces environmental impact consistently across all CGMs.

Further analysis of climate change emissions per component (Fig. 5c) identifies the transmitter as a subsequent hotspot after applicator and packaging reuse (Scenario B). In FL, electronics are embedded within the sensor. For DO and SC, prolonging the lifespan of transmitters can significantly reduce manufacturing-related emissions, particularly those from semiconductors, which account for the majority of electronic component emissions. Design improvements could include rechargeable or replaceable batteries to extend the transmitter's lifecycle. Maximising device usage over its whole lifespan is critical to realising environmental benefits (Kane et al., 2018).

The dominance of TETP and HTPnc across all CGM models highlights that toxicity-related burdens play a central role in the environmental profile of these devices. These impacts arise mainly from upstream emissions associated with polymer production, metal processing, and electronic components, all of which are materials common to applicators, needles, packaging, and transmitters (Tarpani and Gallego-Schmid, 2024). Polymers such as polycarbonate and polypropylene are energy- and chemical-intensive to manufacture, contributing substantially to both ecotoxicity and human toxicity. Likewise, electronic components in the SC-SU transmitter reflect the high toxicity footprint associated with printed circuit boards and metal refining (Tarpani and Gallego-Schmid, 2024). The alignment between midpoint toxicity results and endpoint damage categories underscores that material intensity, particularly in polymers, electronics, and packaging, is a key environmental hotspot. These findings suggest that circular-design strategies focusing on reducing polymer mass, minimising packaging, and extending the life of high-impact components (e.g., applicator bodies or electronic transmitters) could substantially reduce both toxicity-related and endpoint impacts.

The sensitivity analysis shows that variations in manufacturing waste rate and end-of-life treatment assumptions result in only minor changes across midpoint impact categories. Increasing transport distance by 20% has a negligible effect, confirming that logistics is not a key environmental driver for this system. In contrast, the electricity mix used during manufacturing exerts a comparatively larger influence, particularly for climate change-related and toxicity-related indicators. Across all sensitivity scenarios examined, the relative ranking between the single-use and reuse options remains unchanged, indicating robustness of the comparative conclusions.

4.5. Policy and industry implications

The findings of this study indicate that modular design strategies have the potential to deliver larger reductions in environmental impacts than material substitution alone, particularly when evaluated at the system level. However, the feasibility of implementing modular design in medical devices is constrained by stringent regulatory requirements. Under the EU Medical Device Regulation (MDR), any substantial change to device architecture, materials, or reuse requires comprehensive revalidation of safety, performance, and benefit-risk assessment, with associated implications of cost, time and stakeholder approval (Union, 2017). Consequently, implementation of modular design is most aligned with longer-term product innovation, rather than being a strategy which can be rapidly realised in the short-term. This does underline the importance of considering sustainability and modular design *early*, and *throughout*, product development to best embody these principles in new medical products. These outcomes are consistent with circular design principles, and supported by government-level guidelines, notably the UK's Design for Life framework which emphasises the need for durability, modularity, reduced material intensity and improved end-of-life recovery (Department Health and Social Care, 2024).

Within this context, modular design aligns closely with emerging circularity policies in healthcare, including the UK NHS's Net Zero commitment and Net Zero Supplier Roadmap (2022-2028) (National Health Service, 2024). Under the roadmap, suppliers are required to demonstrate an increasing level of carbon accountability across scope 1, 2, and 3 emissions, requiring suppliers to provide product-level carbon footprinting by 2028 (National Health Service, 2024). Similarly, the European Green Deal strategy includes sustainability and packaging regulations that will increasingly affect healthcare and pharmaceutical manufacturers, reinforcing the need for proactive activity to improve sustainability in future device design and manufacturing supply chains (European comission, 2019).

In summary, this study demonstrates that applying CE principles namely, narrowing, slowing, and closing the loops can significantly reduce the environmental impact of CGMs. Narrowing the loop involves reducing resources, such as using lightweight packaging or eliminating non-essential components. Slowing the loop can be achieved by extending the product's useable life, including the implementation of modular design in the applicator, which allows for the reuse of plastic after replacing the needle. Recharging the transmitter or using a replaceable battery could also slow the loop. Finally, closing the loop can be achieved by enhancing recyclability. This can be achieved through thoughtful design choices, such as modular assemblies, clear material labelling, simplified disassembly, and minimized additives mixture. Together, these strategies present a comprehensive approach to designing more sustainable glucose meters.

5. Conclusion

This study confirmed that combining materials composition analysis and life cycle assessment can help identify design strategies to reduce the environmental burden of continuous glucose meter devices. By tracing the movement of materials through the product system and linking these flows to environmental outcomes, it was possible to identify specific parts of the device where design changes yield meaningful reductions in resource use and waste generation. The findings demonstrated that extending the life of key components, reducing unnecessary material input, and enabling easier end-of-life separation decrease the device's overall environmental load. These insights indicate that responsible design interventions should occur early in product development. The novelty of this work lies in the combined analytical approach that guides practical, sustainable design decisions for a small medical device, offering a clear pathway for product development that supports patient safety and global sustainability.

CRediT authorship contribution statement

Zahrina Mardina: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Noeka Bradley:** Investigation, Formal analysis. **Gloria Omurunga:** Investigation, Formal analysis. **Alexander Kulak:** Resources, Funding acquisition, Formal analysis, Data curation. **Rory P. Turnbull:** Writing – review & editing, Methodology. **Shahin Rahimifard:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Richard Bibb:** Writing – review & editing, Supervision, Funding acquisition. **Peter Culmer:** Writing – review & editing, Visualization, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: ZAHRINA MARDINA reports financial support was provided by united kingdom research and innovation (UKRI). ZAHRINA MARDINA reports a relationship with Engineering and Physical Sciences Research Council (EPSRC) that includes: funding grants. Shahin Rahimifard reports a relationship with Engineering and Physical Sciences Research Council (EPSRC) that includes: funding grants. Richard Bibb reports a relationship with Engineering and Physical Sciences Research Council (EPSRC) that includes: funding grants. Peter Culmer reports a relationship with Engineering and Physical Sciences Research Council (EPSRC) that includes: funding grants. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.148076.

Data availability

Data will be made available on request.

References

Amicarelli, V., Bux, C., 2022. Quantifying textile streams and recycling prospects in Europe by material flow analysis. Environ. Impact Assess. Rev. 97. https://doi.org/10.1016/j.eiar.2022.106878.

Avari, P., Lumb, A., Flanagan, D., Rayman, G., Misra, S., Dhatariya, K., Choudhary, P., 2023. Continuous glucose monitoring within hospital: a scoping review and summary of guidelines from the joint British diabetes societies for inpatient care. J. Diabetes Sci. Technol. 17 (3), 611–624. https://doi.org/10.1177/19322968221137338.

Avari, P., Cai, Y., Verma, V., Reddy, M., Srinivasan, M., Oliver, N., 2024. Batteries within diabetes devices: a narrative review on recycling, environmental, and sustainability perspective. J. Diabetes Sci. Technol., 19322968241278374 https://doi.org/10.1177/19322968241278374.

Baars, J., Rajaeifar, M.A., Heidrich, O., 2022. Quo vadisMFA? Integrated material flow analysis to support material efficiency. J. Ind. Ecol. 26 (4), 1487–1503. https://doi.org/10.1111/jiec.13288.

Basu, P., Jamasb, T., Sen, A., 2024. Trilemma or Trinity? The nexus of economic growth, circular economy and net zero. Energy Econ. 138. https://doi.org/10.1016/j.eneco.2024.107844.

Bhutta, Mahmood, Mulcahy, Elaine, Rizan, Chantelle, Kumar, Shashank, Floyd, Catherine, Steinbach, Ingeborg, Wilson, Jennie, Winter Beatty, Jasmine, Pegg, M., 2023. Green Surgery-Reducing the Environmental Impact of Surgical Care. Green Surgery – UK Health Alliance on Climate Change.

Brändström, J., Eriksson, O., 2022. How circular is a value chain? Proposing a material efficiency metric to evaluate business models. J. Clean. Prod. 342. https://doi.org/10.1016/j.jclepro.2022.130973.

Chowdhury, T.A., Stefanova, S., Bennett-Richards, P., 2024. Sustainable practice: insulin therapy. Br. Med. J. 387, e079425. https://doi.org/10.1136/bmj-2024-079425.

Cilleruelo Palomero, J., Freboeuf, L., Ciroth, A., Sonnemann, G., 2024. Integrating circularity into life cycle assessment: circularity with a life cycle perspective. Clean. Environ. Syst. 12. https://doi.org/10.1016/j.cesys.2024.100175.

Contreras-Zarazúa, G., Vázquez-Castillo, J.A., Ramírez-Márquez, C., Segovia-Hernández, J.G., Alcántara-Ávila, J.R., 2017. Multi-objective optimization involving cost and control properties in reactive distillation processes to produce diphenyl carbonate. Comput. Chem. Eng. 105, 185–196. https://doi.org/10.1016/j.compchemeng.2016.11.022.

Czuba, L., 2014. Application of plastics in medical devices and equipment. In: Handbook of Polymer Applications in Medicine and Medical Devices, pp. 9–19. https://doi.org/10.1016/b978-0-323-22805-3.00002-5.

Department Health and Social Care, D., 2024. Design for Life Roadmap.

Didyuk, O., Econom, N., Guardia, A., Livingston, K., Klueh, U., 2021. Continuous glucose monitoring devices: past, present, and future focus on the history and evolution of technological innovation. J. Diabetes Sci. Technol. 15 (3), 676–683. https://doi.org/10.1177/1932296819899394.

Edward, R., Priefer, R., 2023. A comparison of continuous glucose monitors (CGMs) in diabetes management: a systematic literature review. Prim Care Diabetes. https://doi.org/10.1016/j.pcd.2023.10.009.

European comission, E., 2019. The European Green Deal.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manag. 91 (1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018.

Fukuoka, S., Fukawa, I., Adachi, T., Fujita, H., Sugiyama, N., Sawa, T., 2019. Industrialization and expansion of green sustainable chemical process: a review of non-phosgene polycarbonate from CO2. Org. Process Res. Dev. 23 (2), 145–169. https://doi.org/10.1021/acs.oprd.8b00391.

Garg, S.K., 2023. Past, present, and future of continuous glucose monitors. Diabetes Technol. Therapeut. 25 (S3), S1–S4. https://doi.org/10.1089/dia.2023.0041.

Gargasson, P.L., Pelcat, M., Beuve, N., Pressigout, M., Morin, L., Menard, D., 2025. *PCBnCO: a carbon intensity model of FR-4 printed circuit boards based on Company data* 2025. IEEE Conference on Technologies for Sustainability (SusTech).

Gonçalves, M., Freire, F., Garcia, R., 2024. Material flow analysis and circularity assessment of plastic packaging: an application to Portugal. Resour. Conserv. Recycl. 209. https://doi.org/10.1016/j.resconrec.2024.107795.

Gradin, K.T., Björklund, A., 2020. The common understanding of simplification approaches in published LCA studies—a review and mapping. Int. J. Life Cycle Assess. 26 (1), 50–63. https://doi.org/10.1007/s11367-020-01843-4.

Greener, M., 2023. The greening of diabetes. Pract. Diabetes 40 (2), 8–10. https://doi.org/10.1002/pdi.2442.

Guzzo, D., Carvalho, M.M., Balkenende, R., Mascarenhas, J., 2020. Circular business models in the medical device industry: paths towards sustainable healthcare. Resour. Conserv. Recycl. 160. https://doi.org/10.1016/j.resconrec.2020.104904.

Heinemann, L., Klonoff, D.C., 2022. Diabetes technology and waste: a complex story. J. Diabetes Sci. Technol. 16 (6), 1381–1384. https://doi.org/10.1177/19322968211022321.

Hosseinian, A., Johansson, A., Karvonen, J., Nissinen, A., Pitkanen, A., Sokka, L., 2025. Comparative carbon footprint study of self-monitoring Vs. Continuous monitoring of blood glucose. Glob. Chall. 9 (9), e00118. https://doi.org/10.1002/gch2.202500118.

Hoveling, T., Svindland Nijdam, A., Monincx, M., Faludi, J., Bakker, C., 2024. Circular economy for medical devices: barriers, opportunities and best practices from a design perspective. Resour. Conserv. Recycl. 208. https://doi.org/10.1016/j.resconrec.2024.107719.

Iacobucci, G., 2021. One in 10 UK adults could have diabetes by 2030, warns charity. Br. Med. J. 375, n2453. https://doi.org/10.1136/bmj.n2453.

International council on clean transportation, I, 2017. A Technical Summary of Euro 6/VI Vehicle Emission Standards. Retrieved from. www.theicct.org.

International Diabetes Foundation, I, 2025. Diabetes Atlas.

International standard organization, I., 2006. In: International Standard Organization. ISO 14044.

Jaime, Sandra B.M., Alves, Rosa M.V., Bócoli, P.F.J., 2022. Moisture and oxygen barrier properties of glass, PET and HDPE bottles for pharmaceutical products. J. Drug Deliv. Sci. Technol. 1773–2247. https://doi.org/10.1016/j.jddst.2022.103330.

Jendrike, N., Link, M., Oter, S., Fei, J., Zheng, J., Gao, F., Gao, A., Zhu, S., Shi, L., Strange, P., Flacke, F., Eichenlaub, M., Freckmann, G., 2025. Performance of a new continuous glucose monitoring system in German adults living with diabetes. Diabetes Ther. https://doi.org/10.1007/s13300-025-01832-6.

Kane, G.M., Bakker, C.A., Balkenende, A.R., 2018. Towards design strategies for circular medical products. Resour. Conserv. Recycl. 135, 38–47. https://doi.org/10.1016/j.resconrec.2017.07.030.

Kiemel, S., Rietdorf, C., Schutzbach, M., Miehe, R., 2022. How to simplify life cycle assessment for industrial applications—A comprehensive review. Sustainability 14 (23). https://doi.org/10.3390/su142315704.

Klonoff, D.C., Heinemann, L., Cook, C.B., Thompson, B.M., Kerr, D., Han, J., Krisiunas, E. P., 2020. The diabetes technology society green diabetes initiative. J. Diabetes Sci. Technol. 14 (3), 507–512. https://doi.org/10.1177/1932296820904175.

Kristensen, H.S., Mosgaard, M.A., 2020. A review of micro level indicators for a circular economy – moving away from the three dimensions of sustainability? J. Clean. Prod. 243. https://doi.org/10.1016/j.jclepro.2019.118531.

Lopes, V., Sousa Lages, A., 2022. Waste associated to diabetes management: the elephant in the room of technology? Diabetes Res. Clin. Pract. 185, 109780. https://doi.org/10.1016/j.diabres.2022.109780.

Lupton, R.C., Allwood, J.M., 2017. Hybrid Sankey diagrams: visual analysis of multidimensional data for understanding resource use. Resour. Conserv. Recycl. 124, 141–151. https://doi.org/10.1016/j.resconrec.2017.05.002.

Martin-Cabezuelo, R., Vilarino-Feltrer, G., Campillo-Fernandez, A.J., Lorenzo-Zuniga, V., Pons, V., Lopez-Munoz, P., Tort-Ausina, I., 2024. Materials science toolkit for carbon footprint assessment: a case study for endoscopic accessories of common use. ACS Environ. Au 4 (1), 42–50. https://doi.org/10.1021/acsenvironau.3c00044.

Miller, E.A., Yamahara, K.M., French, C., Spingarn, N., Birch, J.M., Van Houtan, K.S., 2022. A raman spectral reference library of potential anthropogenic and biological ocean polymers. Sci. Data 9 (1), 780. https://doi.org/10.1038/s41597-022-01883-5.

Na, H., Qiu, Z., Sun, J., Yuan, Y., Zhang, L., Du, T., 2024. Revealing cradle-to-gate CO2 emissions for steel product producing by different technological pathways based on material flow analysis. Resour. Conserv. Recycl. 203. https://doi.org/10.1016/j.resconrec.2024.107416.

National Health Service, N., 2024. NHS-Net-Zero-Supplier-Roadmap-2024.

National Institute for Health and Care Excellence, N, 2022. Type 1 Diabetes in Adults: Diagnosis and Management. National Institute for Health and Care Excellence (NICE).

Negrete-Bolagay, D., Guerrero, V.H., 2024. Opportunities and challenges in the application of bioplastics: perspectives from formulation, processing, and performance. Polymers 16 (18). https://doi.org/10.3390/polym16182561.

Nguyen, K.T., Xu, N.Y., Zhang, J.Y., Shang, T., DuBord, A.Y., Heinemann, L., Krisiunas, E. P., Stumpe, T., Seid, D.A., Klonoff, D.C., 2022. Green diabetes summit 2021. J. Diabetes Sci. Technol. 16 (1), 233–247. https://doi.org/10.1177/19322968211049800.

NHS, D., 2023. Prescribable Continuous Glucose Monitoring.

Ohms, P.K., Horup, L.H., Gummidi, S.R.B., Ryberg, M., Laurent, A., Liu, G., 2024. Temporally dynamic environmental impact assessment of a building stock: coupling MFA and LCA. Resour. Conserv. Recycl. 202. https://doi.org/10.1016/j.resconrec.2023.107340.

Olczuk, D., Priefer, R., 2018. A history of continuous glucose monitors (CGMs) in self-monitoring of diabetes mellitus. Diabetes Metabol. Syndr. 12 (2), 181–187. https://doi.org/10.1016/j.dsx.2017.09.005.

Petry, S.F., Bienhaus, M., Petry, F.W., Petry, J.K., Heinemann, L., Gath, S., 2024. Quantification of different types of waste and batteries associated with the widespread usage of continuous glucose monitoring systems. J. Diabetes Sci. Technol., 19322968241305161 https://doi.org/10.1177/19322968241305161.

Petry, S.F., Petry, F.W., Petry, J.K., Gath, S., Heinemann, L., 2025. Diabetes technology and waste: a real-world study in a specialized practice in Germany. J. Diabetes Sci. Technol. 19 (6), 1561–1569. https://doi.org/10.1177/19322968241257004.

Rizan, C., Brophy, T., Lillywhite, R., Reed, M., Bhutta, M.F., 2022. Life cycle assessment and life cycle cost of repairing surgical scissors. Int. J. Life Cycle Assess. 27 (6), 780–795. https://doi.org/10.1007/s11367-022-02064-7.

Samani, P., 2023. Synergies and gaps between circularity assessment and life cycle assessment (LCA). Sci. Total Environ. 903, 166611. https://doi.org/10.1016/j.scitotenv.2023.166611.

Samuel, A.Z., Mukojima, R., Horii, S., Ando, M., Egashira, S., Nakashima, T., Iwatsuki, M., Takeyama, H., 2021. On selecting a suitable spectral matching method for automated analytical applications of raman spectroscopy. ACS Omega 6 (3), 2060–2065. https://doi.org/10.1021/acsomega.0c05041.

Sastri, V.R., 2014. Material requirements for plastics used in medical devices. In: Plastics in Medical Devices, pp. 33–54. https://doi.org/10.1016/b978-1-4557-3201-2.00004-5.

Sgambaro, L., Kaipainen, J., Chiaroni, D., 2025. Scaling up circular ecosystems through product design practices: an integrative framework. Comput. Ind. Eng. 204. https://doi.org/10.1016/j.cie.2025.111073.

Tarpani, R.R.Z., Gallego-Schmid, A., 2024. Environmental impacts of a digital health and well-being service in elderly living schemes. Clean. Environ. Syst. 12. https://doi.org/10.1016/j.cesys.2023.100161.

Tascione, V., Simboli, A., Taddeo, R., Del Grosso, M., Raggi, A., 2024. A comparative analysis of recent life cycle assessment guidelines and frameworks: methodological evidence from the packaging industry. Environ. Impact Assess. Rev. 108. https://doi.org/10.1016/j.eiar.2024.107590.

Tian, T., Ho, C.N., Ayers, A.T., Aaron, R.E., Klonoff, D.C., Ahn, D.T., Kerr, D., Peters, A.L., Philis-Tsimikas, A., Shah, V.N., Herndon, E.G., Yang, Y., Li, C., Wang, J., 2025. Quantifying environmental waste from diabetes devices in the U.S. Diabetes Care 48 (7), 1198–1203. https://doi.org/10.2337/dc24-2522.

Union, E., 2017. EU Medical Device Regulations (MDR).

Yang, C., Wang, B., Wan, J., Kamath, A., You, F., Tian, B., 2026. Quantifying the global eco-footprint of wearable healthcare electronics. Nature 649 (8095), 73–82. https://doi.org/10.1038/s41586-025-09819-w.

Yao, Z., Seong, H.J., Jang, Y.S., 2022. Environmental toxicity and decomposition of polyethylene. Ecotoxicol. Environ. Saf. 242, 113933. https://doi.org/10.1016/j.ecoenv.2022.113933.

Zhang, T., Bainbridge, A., Harwell, J., Zhang, S., Wagih, M., Kettle, J., 2024. Life cycle assessment (LCA) of circular consumer electronics based on IC recycling and emerging PCB assembly materials. Sci. Rep. 14 (1), 29183. https://doi.org/10.1038/s41598-024-79732-1.

Zhou, X., Zhai, Y., Ren, K., Cheng, Z., Shen, X., Zhang, T., Bai, Y., Jia, Y., Hong, J., 2023. Life cycle assessment of polycarbonate production: proposed optimization toward sustainability. Resour. Conserv. Recycl. 189. https://doi.org/10.1016/j.resconrec.2022.106765.