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Mapping circular economy product and material flows in healthcare: A visual taxonomy

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A B S T R A C T

Background: The healthcare sector contributes substantially to environmental pollution, affecting ecosystems and public health. Circular economy (CE) strategies offer potential solutions, but existing frameworks provide limited guidance for healthcare, overlooking factors such as infection control, decontamination, and staff workload.

Methods: We developed the *Circular Healthcare Flows visual*, a taxonomy of CE strategies for medical devices, using observations in sterilization departments, recycling facilities, and manufacturing plants; 21 expert interviews; and a systematic review of 1104 studies (68 full-text reviews). Additional stakeholder feedback validated and refined the taxonomy.

Findings: The taxonomy identifies 13 CE strategies—refuse, replace, rethink, reduce, reuse, maintain, repair, refurbish, remanufacture, repurpose, recycle, renew, and recover—and organizes them in a healthcare-specific framework. Iterative feedback ensured that the taxonomy is clear, practically applicable, and addresses sector-specific regulatory, clinical, and operational constraints.

Interpretation: The *Circular Healthcare Flows visual* provides a practical tool to standardize terminology and guide the implementation of CE strategies in healthcare. By offering conceptual structure and actionable guidance, it supports informed decision-making, facilitates collaboration among stakeholders, and encourages consistent application of circular strategies across the sector.

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1. Introduction

The healthcare sector is essential for improving and maintaining health, yet it contributes 4–5 % of global greenhouse gas emissions (Rodríguez-Jiménez et al., 2023), paradoxically undermining societal health. A 1 % increase in carbon emissions can increase inpatient visits by 0.162 % and outpatient visits by 0.298 % (Dong et al., 2021). According to the 2024 *Quantifying the Impact of Climate Change on Human Health* report (World Economic Forum, 2024), climate change is projected to cause 14.5 million additional deaths worldwide by 2050, further exacerbating the strain on global healthcare systems.

Healthcare systems themselves are major contributors to environmental degradation due to energy-intensive operations, high material throughput, and complex waste streams. Studies by Eckelman and Sherman (2016) (Eckelman and Sherman, 2016), Eckelman and McGain (2020) (Eckelman et al., 2020), and others have quantified healthcare's carbon footprint and emphasized the need for systemic mitigation strategies across supply chains, clinical operations, and procurement. Initiatives such as *Health Care Without Harm* and *Practice Greenhealth* demonstrate that integrating environmental management principles—energy efficiency, waste minimization, and product life extension—can reduce emissions while maintaining quality of care. These approaches form a theoretical and practical bridge between sustainability science and circular economy thinking within healthcare.

This study tackles how circular economy (CE) principles can be made workable within healthcare, a field where sector-specific and operationally detailed CE frameworks remain limited. CE strategies, which promote the reuse, remanufacturing, and recycling of products and materials (Kane et al., 2018), shift away from linear production and consumption toward regenerative systems that reduce waste, preserve

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product value, and support economic resilience. While CE overlaps with environmental sustainability, it is distinct: CE focuses on closing material loops and retaining product value, whereas sustainability addresses broader issues like carbon footprint reduction and biodiversity conservation. In this study, "circular economy (CE)" or "circularity" is used to engage with the broader discourse on resource recovery and waste reduction.

To operationalize CE in healthcare, it is necessary to examine existing CE frameworks and assess their applicability to sector-specific challenges. Among the most recognized frameworks is the Ellen MacArthur Foundation's (EMF) Butterfly Diagram (Ellen MacArthur Foundation, 2019), which divides CE into a technical cycle (reuse, repair, recycling) and a biological cycle (composting, anaerobic digestion). Similarly, the Netherlands Environmental Assessment Agency's (PBL) 10R-strategies framework (Potting et al., 2017) categorizes circular strategies from "refuse" (R0) to "recover" (R9), providing a structured hierarchy. In contrast, The Value Hill model (Achterberg et al., 2016), developed by Nuovalente, Circle Economy, Sustainable Finance Lab, TU Delft, and Het Groene Brein, examines value retention across product lifecycles. Additionally, the "Re-defining Value" report from the United Nations Environment Programme (UNEP) and International Resource Panel (IRP) (United Nations Environment Programme and International Resource Panel, 2018) complements these frameworks by providing insights into material and product lifecycle management.

When applying circular economy (CE) models to healthcare systems, these general frameworks must be adapted to address sector-specific sustainability challenges such as infection control, contamination risk, and regulatory barriers to reuse. These issues are extensively discussed in the literature on sustainable healthcare management. Applying CE in healthcare requires a systems-thinking approach that considers interactions across material flows, clinical operations, stakeholder behaviour, and regulatory frameworks. For example, MacNeill et al. (2020) (MacNeill et al., 2020) highlight barriers such as assumptions about infection prevention and the behaviours of healthcare professionals, while Hoveling et al. (2024) (Hoveling et al., 2024a) identify perceived safety and infection risks, as well as regulatory difficulties, as major obstacles to circular medical device design. Together, these studies emphasize that healthcare requires tailored CE strategies that reconcile sustainability goals with patient safety and regulatory compliance, and that provide clear, practical guidance for safely reintegrating medical materials and devices into circular loops. Viewed within hospital sustainability literature, these studies indicate that circular strategies can extend existing environmental management efforts, improving material retention and waste reduction.

In addition to the just-mentioned conceptual frameworks, non-healthcare related regulatory and standardization efforts have also attempted to define CE principles more formally. ISO 59004:2024 () provides standardized definitions for key CE terms while emphasizing systemic thinking, value retention, and stakeholder collaboration. Meanwhile, the Waste Framework Directive (WFD) (Directive, 2008, 2018) establishes a waste hierarchy prioritizing prevention, reuse, recycling, and recovery. However, neither ISO 59004:2024 nor the WFD directly address the management of hazardous and bio-contaminated waste, which is a critical consideration in healthcare settings. Healthcare regulatory frameworks like the US Food and Drug Administration (FDA) (Center for Devices and Radiological Health, 2020) and the EU Medical Device Regulations (MDR) (MDR-EU, 2017, 2017) impose strict guidelines on medical device safety and reuse. Interestingly, both refer to "reprocessing" as a CE strategy—a term that is absent from several widely recognized non-healthcare CE frameworks, including the Butterfly Diagram (Ellen MacArthur Foundation, 2019), Value Hill model (Achterberg et al., 2016), 10R framework (Potting et al., 2017), ISO 59004:2024 (), and Waste Framework Directive (WFD) (Directive, 2008, 2018).

Moreover, the instance of terminology confusion surrounding "reprocessing" is just one example among many documented in the literature. Chang et al. note that "inconsistent terminology regarding sterilization cycles has led to confusion among ambulatory surgery centres," highlighting how such discrepancies can disrupt operational clarity (Chang et al., 2018). Similarly, Peters et al. propose using emojis to bridge language barriers in respirator reprocessing guidelines, underscoring the need for more precise language (Peters et al., 2021). While innovative, such approaches may be limiting in spoken language and when conveying the nuanced distinctions between CE strategies. The lack of standardized terminology complicates communication among stakeholders and may hinder transdisciplinary research, which, according to Uiterkamp and Vlek (2007), is crucial for advancing circularity (Uiterkamp and Vlek, 2007). These examples illustrate a broader challenge: divergent language across disciplines hampers interdisciplinary collaboration and the successful implementation of circular economy strategies. This is important, as the practical application of CE strategies in healthcare is further challenged by conflicting stakeholder priorities—such as safety, sales, and regulatory approval—which can overshadow environmental objectives (Kane et al., 2018). Effective collaboration among these diverse groups is therefore essential for aligning interests and implementing circular strategies.

This terminology challenge extends beyond text-based definitions. Use of visualization (including e.g. emojis, as was suggested by Peters et al. (2021)) could offer benefits in overcoming language barriers and improving collaboration. As described by Eppler and Bresciani in 2013, using qualitative visualisations such as conceptual diagrams, metaphors and sketches could in fact enable effective and seamless collaboration across disciplinary boundaries (Eppler and Bresciani, 2013). In 2019, Bresciani developed a framework for collaborative dimensions of visualizations (Bresciani, 2019). While focused on developing visuals in smaller group collaborations (in comparison to the circular healthcare sector), her framework does detail seven dimensions that can be relevant for constructing conceptual visualizations to support collaboration: structural restrictiveness (extent to which the design process is guided or constrained by the visualization), content modifiability (extent to which the items of a visualization can be dynamically changed), directed focus (extent to which the main item(s) of the discussion is visually emphasized), perceived "finishedness" (extent to which visual cues suggest whether an object appears finished), outcome clarity (extent to which a visual representation is self-explanatory and easily understandable with low cognitive effort), visual appeal (extent to which a visual representation is attractive and pleasant to the eyes), and collaboration support (extent to which a visualization controls the flow of group discussion).

Some attempts have been made to develop visualizations of the CE, such as the previously-discussed butterfly diagram (Ellen MacArthur Foundation, 2019). Likewise, the European Union's interactive Sankey diagrams (Chang et al., 2018) provide a visual tool with insights into CE material flows, mapping extraction, consumption, and recycling pathways. However, both visualizations could be improved based on the collaborative dimensions of visualizations framework. For example, the Butterfly Diagram seems to unintentionally draw attention to regeneration of waste in the biosphere and is not fully self-explanatory due to the lack of detail. Likewise, the Sankey diagrams are very focused on material flows alone, while also not being very intuitive to use with low cognitive effort. Additionally, like other general CE frameworks, they fall short of addressing sector-specific needs in healthcare, such as balancing circular strategies with infection control and clinical effectiveness.

To address these challenges, this study aims to develop the *Circular Healthcare Flows visual*—a visual taxonomy that applies established circular economy principles within healthcare-specific constraints. The visual taxonomy is designed as both a conceptual and practical tool for healthcare stakeholders—including designers, clinicians, procurement teams, remanufacturers, and policymakers—to apply circular strategies while safeguarding patient safety, infection control, and regulatory compliance. It was developed iteratively, drawing on field observations, expert feedback, and a systematic review of how circularity is discussed

in healthcare literature. The framework also draws inspiration from Bresciani's collaborative dimensions to strengthen clarity, adaptability, and usability in multidisciplinary settings. Together, these elements aim to create a visual that is genuinely useable in healthcare practice rather than a generic circularity model.

2. Method

The *Circular Healthcare Flows visual* was developed through a stepwise, iterative process (Table 1). Initially, internal circular economy (CE) expertise at TU Delft was used to draft a first version of the system visual, forming the basis for further iteration. This initial version was refined through observational research, which helped map procedural steps for each CE strategy and incorporate healthcare-specific nuances, informing early iterations (3–4, Table 1).

The visual at that stage was used as a research probe in expert interviews, allowing participants to provide practical feedback and highlight areas needing improvement (iterations 5–7, Table 1). During these interviews, it became clear that there was no consensus on CE strategies, terminology, or definitions, indicating a need for a systematic literature review to ensure standardization and evidence-based terminology.

The systematic literature review was then conducted to standardize terminology, clarify definitions, and refine the sequencing of CE strategies in the visual (iterations 9–10, Table 1). After revising the visual based on the literature review findings, it was validated again with the same and additional experts, ensuring both accuracy and practical relevance (iterations 13–14, Table 1).

Finally, once content-related aspects were finalized, the visual was refined and evaluated using the Collaborative Dimensions Framework, optimizing clarity, focus, modifiability, usability, and collaboration support across seven clearly defined dimensions: visual impact, clarity, perceived finishedness, directed focus, inference support, modifiability, and discourse management. Insights from each stage informed subsequent iterations, linking evidence collection directly to design refinements.

The development combined observational research, expert interviews, systematic literature review, and stakeholder validation, with each method feeding into the next in a clearly sequenced, iterative process that informed the final visual taxonomy. Each method's contribution to the iterative development is explicitly linked to the corresponding updates in Table 1.

Table 1
Overview of *Circular Healthcare Flows visual* iterations.

#	Intention of specific iteration	Developed based on
1	Exploration and defining literature and observation strategy	Internal knowledge TU Delft
2	Update based on new findings	Initial literature search
3	Update based on new findings	Observational research (see paragraph 2.1)
4	Update graphical design for final research probe	Internal consultations
5	Corrections based on new findings	Expert interviews (see paragraph 2.2)
6	Corrections based on new findings	Expert interviews (see paragraph 2.2)
7	Corrections based on additional feedback	Expert interviews (see paragraph 2.2)
8	Improve clarity and identify additional knowledge gaps	Internal consultations
9	Adapt terminology and definitions used	Early literature review findings (see paragraph 2.3)
10	Adapt terminology and definitions used	Final literature review findings (see paragraph 2.3)
11	Add additional contextual information where needed	Internal consultations
12	Improve graphical design to fit newly added strategies	Internal consultations
13	Corrections based on additional feedback	Validation with experts (see paragraph 2.4)
14	Final validated version (minimal final corrections)	Validation with experts (see paragraph 2.4)

2.1. Observational research

Observational research aimed to map procedural steps for each CE strategy and identify healthcare-specific nuances, ensuring that the visual taxonomy reflects real-world operational practices. Site visits included a recycling facility (~2 h), a medical device production site (~2 h), various clinical procedure areas in hospitals (~10–12 h total across multiple departments), and three internal and two external hospital sterilization departments (~1 h per facility). Notes and photographs from these visits were analysed and translated into visual representations, informing both content and design decisions in the taxonomy. A total of 8 site visits were conducted, covering diverse healthcare and industrial settings. This number was considered sufficient to capture the key procedural variations across different settings, allowing the development of a first version of the visual taxonomy that could then be iteratively refined based on expert interviews. These observations ensured that the visual accurately reflected real-world processes and practical considerations across multiple healthcare contexts. To enhance consistency, observations were documented systematically through structured notes and photographs, with key patterns discussed among the research team before translating them into visual representations.

2.2. Expert interviews

Expert interviews aimed to gather sector-specific insights to refine and validate the visual taxonomy, ensuring practical relevance and clarity per CE strategy. The visual probe (Appendix A) was used to elicit feedback on content, terminology, and usability. Procedural details (e.g., transcription tools, platforms) have been summarized here; full protocols are in Appendix B. The research probe was developed by combining observational research findings with internal knowledge from the Sustainable Design Engineering department at TU Delft and further refined using literature and observations. Literature sources included general CE principles and strategies, such as the PBL 10R-strategies framework and the EMF butterfly diagram, which informed the initial visual overview.

The interview participants (Table 2) were those previously published in (Hoveling et al., 2024a), which reported the second part of the same interview, which will not be repeated in this paper. Thirty-four experts divided over twenty-one interviews, from a variety of EU countries (The Netherlands, Switzerland, Spain, Norway, Slovenia) and the USA took part (Table 2). Interview participants were selected to represent a diverse range of backgrounds and expertise. For each of the categories—sterilization facilities (internal and external), manufacturers, hospital procurement, (international) foundations, (hazardous) waste handling, collection systems experts, recycling facilities, remanufacturing experts, and biocycle or renewable energy experts—the goal was to conduct at least two interviews, with each interview including one to three individuals. No participant took part in more than one interview. Participants (hereafter referred to as 'experts' or 'stakeholders' depending on context) signed consent forms, and interviews lasted ~30 min via face-to-face or online video call. All sessions were recorded, transcribed with Sonix.ai, and proofread. Coding was performed in ATLAS.ti. Highlighted statements from the interviews were translated into actionable updates to the visual. Although no formal intercoder procedure was applied, the coding reflects the literal statements of the interview participants. Reliability of the coding and interpretations was ensured through a multi-step process: the coded data were visualized in an updated taxonomy, discussed with participants for corrections and refinements, and reviewed again during the formal validation stage (section 2.4).

Table 2
List of expert interview participants.

#	Participant category	Expertise	Number of people in the interview
P1	Sterilization facilities	External sterilization	2
P2	Sterilization facilities	Internal sterilization	1
P3	Manufacturers	Engineering, supply chain, and parts harvesting	2
P4	Manufacturers	Design Engineering	2
P5	Manufacturers	Strategy and design engineering	3
P6	Manufacturers	Research and development	1
P7	Hospital procurement	Academic hospital procurement	1
P8	Hospital procurement	Non-academic hospital procurement	1
P9	Hospital procurement	Non-academic hospital procurement, and intensive care	2
P10	(International) foundations	Sustainable use of natural resources	3
P11	(International) foundations	E-waste responsibility	3
P12	(International) foundations & (hazardous) waste handling	E-waste handling, and recycling	2
P13	Collection systems developer	Circularity collection systems	1
P14	Collection systems developer & recycling facilities	Recycling & collection	1
P15	Recycling facilities	Metal and electronics recycling	1
P16	Recycling facilities & (hazardous) waste handling	Plastics recycling	1
P17	(Hazardous) waste handling	Waste handling policies & practices, and handling sharps	3
P18	Remanufacturing experts	Remanufacturing of construction machines, and circular business concepts	1
P19	Remanufacturing experts	Remanufacturing of devices and components, and relevant regulations	1
P20	Bio cycle/reduce experts	Design engineering, bio-design and biomaterials	1
P21	Bio cycle/reduce experts	Expert on bio cycle processes, and material choices	1

2.3. Systematic literature review

The systematic literature review aimed to address inconsistent terminology and definitions of CE strategies in healthcare and to inform evidence-based development of the *Circular Healthcare Flows visual*. In total, 1104 articles were screened, including 68 full-text review articles analysed in detail. The review had three main objectives:

1. Map terminology usage: Bibliometric analyses were performed to identify term frequency, co-occurrence, and topic clusters, revealing common concepts and knowledge gaps.
2. Compare with frameworks: Terms and definitions were compared to regulatory and CE frameworks—including the 10R framework, EMF Butterfly Diagram, ISO standards, and EU/FDA regulations—to ensure healthcare-specific relevance.
3. Inform visual taxonomy: Insights guided standardization of definitions, alignment of CE strategies with healthcare contexts, and sequencing of steps in the visual taxonomy.

This review was registered at https://osf.io/8psdh and conducted following Cochrane Collaboration methods and PRISMA guidelines (Rethlefsen et al., 2021; Moher et al., 2009). The search strategy was developed and duplicates removed by an information specialist [WB], initially optimized in Embase.com, then adapted for Medline ALL and Web of Science.

2.3.1. Search methods

Searches were conducted in three databases:

- Medline ALL (Ovid, 1946–Daily Update)
- Embase.com (1971–present)
- Web of Science Core Collection (1975–present, including various indexes)

The initial search was performed in January 2023, updated on February 23, 2023 following Bramer's methods (Bramer and Bain, 2017), and a second update was conducted on August 15, 2024 to incorporate additional terms identified during synthesis. Conference abstracts prior to 2020 and articles focused on DNA or tissue repair were excluded. Full search strings are detailed in Appendix D.

2.3.2. Eligibility criteria

Studies were included if they addressed circularity or environmental sustainability of materials, devices, consumables, or products used clinically. Only review articles were analysed in full text; other study designs were included for preliminary bibliometric mapping. Exclusions applied to regenerative materials, tissue repair, and non-environmental sustainability topics.

2.3.3. Study selection

References were imported into EndNote, and duplicates were removed by the information specialist following Bramer's methods (Bramer, 2018). Title and abstract screening were performed in Rayyan, a web-based systematic review tool.

- A pilot screening was performed collectively and individually on a subset of titles/abstracts to refine inclusion and exclusion criteria.
- Two researchers independently screened all remaining titles/abstracts, with discrepancies resolved by a third reviewer.
- Articles with uncertainty were discussed in team meetings to ensure consensus.
- Reasons for exclusion at the title/abstract phase are presented in the PRISMA chart (Fig. 1).

Full-text review was conducted for 68 articles meeting inclusion criteria. Studies not meeting inclusion criteria during full-text review (e.g., reuse of surgical sites instead of materials) were excluded.

2.3.4. Data extraction and synthesis

A multi-stage data extraction process ensured accuracy and reliability:

1. One researcher reviewed the full dataset.
2. Two additional extractors performed quality assurance checks.
3. A fourth extractor randomly verified 10 % of studies.
4. Discrepancies were resolved through team discussion.

Extracted data included:

- Article characteristics (title, year, journal, authors)
- Review method and objectives
- Object of interest (e.g., medical device, consumable, product)
- Sustainability or circularity terms and definitions

Prior to full-text synthesis, bibliometric analyses were conducted on all 1104 articles using VOSviewer to visualize term occurrences, topic

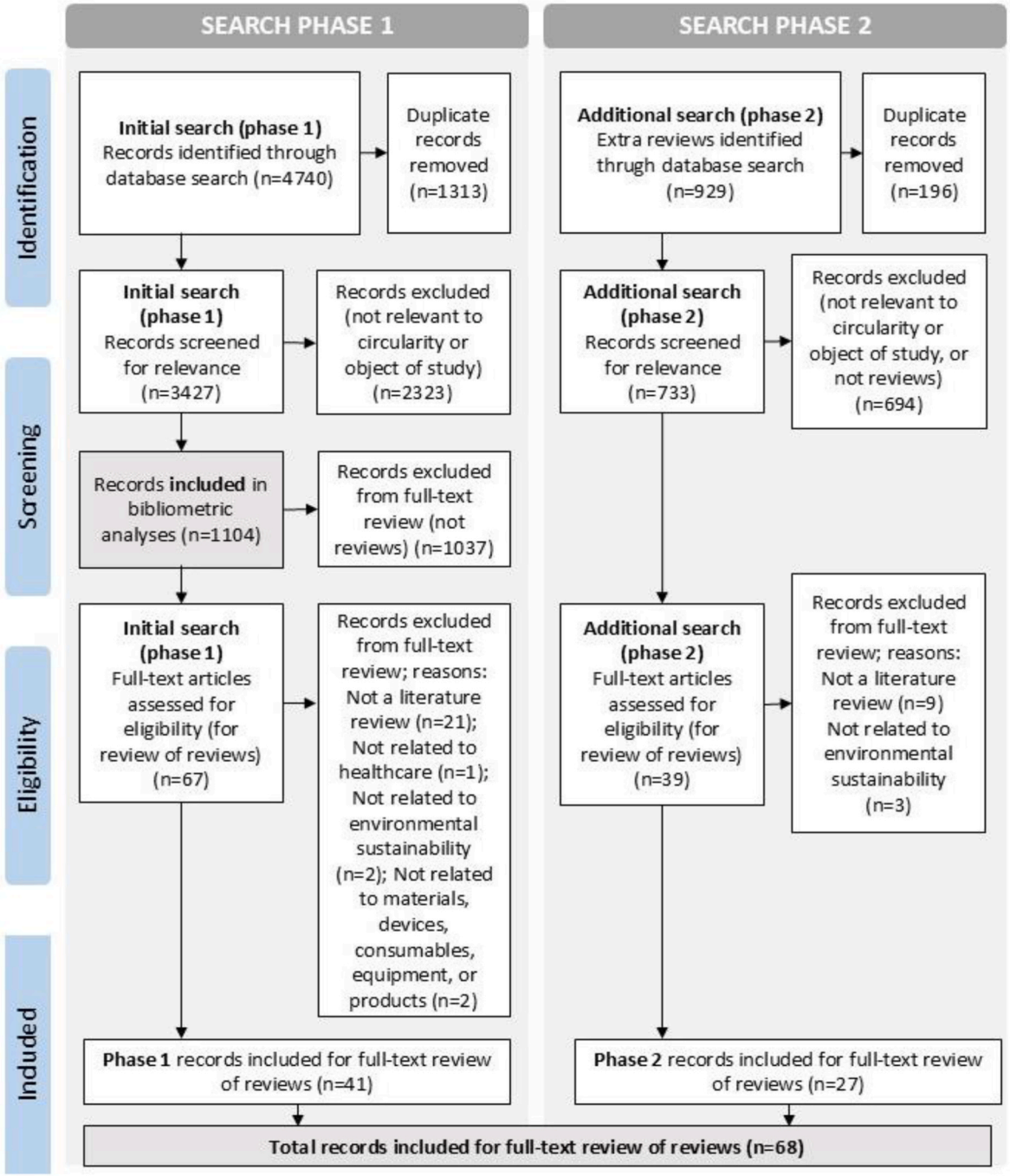

Fig. 1. PRISMA flow diagram for the scoping review process. Adapted from: Peters et al., 2015; Joanna Briggs Institute Reviewers' Manual.

clusters, and co-authorship networks. A thesaurus was applied to standardize terms, remove irrelevant nouns, and identify co-occurrence patterns.

For full-text review, two researchers independently recorded terms and definitions in an Excel file, labelling them as 'clear definition', 'unclear definition', or 'no definition'. Terms with unclear definitions were counted but excluded from detailed analysis. Discrepancies were resolved in team meetings until 100 % consensus was achieved.

All extracted terms and definitions were compared to established healthcare regulations (MDR-EU 2017/745 (MDR-EU, 2017, 2017), FDA (Center for Devices and Radiological Health, 2024)), standards (Waste Framework Directive (Waste Framework Directive), ISO 59004:2024 (), UNEP-IRP (United Nations Environment Programme and International Resource Panel, 2018)), and circular economy frameworks (Butterfly Diagram (Ellen MacArthur Foundation, 2019), 10R framework (Potting et al., 2017), Value Hill (Achterberg et al., 2016)). Overlapping terms were merged, divergent definitions were reevaluated, and insights directly informed the sequencing and development of healthcare-specific definitions in the visual taxonomy.

2.4. *Validation with experts*

Validation aimed to confirm that the final visual taxonomy is accurate, operationally relevant, and aligned with stakeholder perspectives. The visual taxonomy (version in Appendix E) was validated with 11 stakeholders across diverse domains, including circular economy project management, circular business models, circular design, medical device sterilization, and sustainable procurement. All feedback was collected

via email, stored, and analysed in a local file. Conflicting feedback from stakeholders was resolved through team discussions, prioritizing alignment with healthcare-specific requirements, CE principles, and patient safety considerations. Iterative validation cycles ensured that the final visual taxonomy integrated all relevant input while maintaining conceptual consistency. The *Circular Healthcare Flows visual* was updated iteratively and re-shared with the same stakeholders until no further comments remained. After finalizing all content-related aspects, the graphic design was refined and evaluated using the collaborative dimensions framework (Bresciani, 2019) to optimize clarity, focus, modifiability, and usability.

The combination of observational research, expert interviews, systematic literature review, and stakeholder validation produced a healthcare-specific, evidence-based visual taxonomy. Iterative refinement cycles and structured evaluation using the Collaborative Dimensions Framework strengthened both conceptual rigor and the visual's practical clarity.

3. Results

3.1. Observational research and expert interviews

Observations helped identify process steps per CE strategy and their variations, particularly in decontamination processes (cleaning, disinfection, sterilization). Despite location differences, a consistent pattern emerged, shaping the initial *Circular Healthcare Flows visual* (Appendix A), later refined through expert interviews.

Analysis of the 214 coded quotations from the expert interview transcripts revealed key insights. The responses were categorized as follows: 60 general comments, 10 related to collection, 9 on depollution processes, 4 on part recovery, 18 discussing recycling, 4 focused on repurposing, 80 on sterilization, and 29 addressing terminology. Overall, participant feedback was largely positive, but experts emphasized the need to clarify how decision-making and hierarchy were represented after collection, stating that "it should better reflect the hierarchy of flows to aid decisions." Several also highlighted the importance of step sequencing, e.g., "disinfection happens after collection," "melting is always the final recycling step," and "repairs occur after sterilization." Terminology confusion was a recurring issue, mentioned in all but one interview, with comments such as "we don't use 'reprocessing,' we just say sterilization," and "definitions are not yet uniform." One participant remarked, "it is really easy to use the wrong definition," highlighting the ambiguity of CE terms in healthcare.

These insights directly informed refinements to the *Circular Healthcare Flows visual* (Appendix C), guiding adjustments to process sequencing, hierarchy representation, and incorporation of clearly defined, standardized CE terminology. This also motivated the subsequent systematic literature review, which aimed to resolve terminology inconsistencies and support evidence-based updates to both the visual and its strategy definitions.

3.2. Systematic literature review

As shown in the PRISMA chart in Fig. 1, for the bibliometric analysis, 1104 articles were included for bibliometric analysis, and 68 review articles were analysed in full to clarify terminology inconsistencies in CE strategies.

3.3. Preliminary bibliometric analysis in VOSviewer

A bibliometric analysis of 1104 articles from the first search phase provided an overview of key terms, co-occurrence patterns, and author networks in healthcare circular economy literature. Fig. 2 visualizes term co-occurrence, revealing three distinct clusters: red (right), focusing on the environmental footprint, industrial production, waste disposal, and recycling; green (upper left), centring on cleaning, decontamination, and reprocessing; and blue (lower left), relating to specific medical devices, specialties, and adverse events associated with reprocessing. Reprocessing, reusability, and recycling as the most prevalent circular economy strategies. The interactive term graph is available here: https://tinyurl.com/yoqxqoys.

The author network analysis showed many distinct research groups, with prolific contributors such as F. McGain, R.A. Kozarek, and M.Th. Linner. While some authors bridge groups, the network remains fragmented. The interactive author graph can be accessed here: https://tinyurl.com/yusqnwff.

3.4. Full-text analysis of review articles

The 68 review articles covered various topics, with some addressing multiple subjects (see Appendix F). The analysis identified 27 CE strategy terms and labelled them according to frequency, definitions, and overlaps. Only terms with full team consensus were included for comparison. A summarized version of these terms is presented in Table 3, showing the term, frequency (n = 68, as also displayed in Fig. 3), key elements from healthcare literature definitions, established definitions, and integration into the final visual taxonomy. The full set of all extracted definitions for each term, including all variations from healthcare literature, healthcare bodies, non-health organizations, and circular economy frameworks, is provided in Appendix G. Table 3 illustrates that common strategies—such as reuse, reduce, recycle, repair, and maintain—are frequently discussed and directly included in the visual taxonomy, whereas other terms, including prevent, (re)design, closing loops, and research, were either too broad, overlapping, or

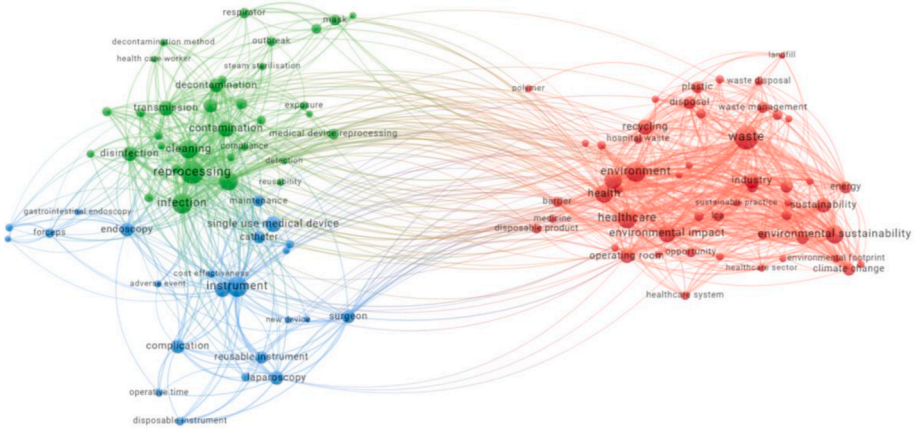

Fig. 2. Co-occurrence of terms visualized in VOSviewer.

Table 3
Condensed summary of 27 healthcare circular economy (CE) strategy terms identified from 68 review articles. Frequency (n = 68), key elements from healthcare literature definitions, established definitions (healthcare bodies/non-health organizations/circular economy frameworks), and integration into the final visual taxonomy are shown. Abbreviations used: FDA = U.S. Food and Drug Administration, MDR = EU Medical Device Regulation, WFD = Waste Framework Directive, ISO = International Organization for Standardization, EMF = Ellen MacArthur Foundation, PBL = Netherlands Environmental Assessment Agency, VH = Value Hill.

Term used for CE strategy	Mentioned by # of articles; n = 68	Key elements from healthcare literature definitions	Established definitions (healthcare bodies/non-health organizations/CE frameworks)	Integration into visual taxonomy
Reuse	**62**	Reuse devices/materials after decontamination; multiple patients; single-patient reuse; materials reuse	**FDA/MDR**: reusable devices can be reprocessed and reused; **WFD/ISO/UNEP/EMF/PBL**: similar definitions	**Included**: 5th strategy
Reduce	**54**	Reduce waste, resources, environmental impact, unnecessary care, unsustainable devices, chemicals/toxins	**PBL:** increase efficiency, consume fewer resources	**Included**: 4th strategy
Recycle	**53**	Recover raw material through processing: decontaminate, shred, melt, remould	**FDA/WFD/ISO/UNEP/EMF/PBL/VH:** processing of waste into new products/materials	**Included**: 11th strategy
Reprocess	**48**	Decontaminate, clean, sterilize; prepare used devices for reuse	**MDR/FDA:** safe reuse including cleaning, disinfection, sterilization	**Overarching term:** reuse, maintain, repair, refurbish, remanufacture
Prevent	**32**	Prevent unnecessary care, device use, waste, infection, environmental impact	**WFD:** measures to reduce waste/impact before product becomes waste	**Partially grouped**: under refuse, replace, reduce; not independent
(Re)design	**32**	Design for sustainability/circularity, sterilization, waste reduction, recyclability, durability, eco-design, modularity, maintenance, refurbishment, end-of-life	**ISO:** eco-design and circular design; **VH:** design for end-of-life	**Partially grouped**: under other strategies (too broad)
Replace	**31**	Substitute devices, materials, or procedures with more sustainable alternatives, digitization, parts replacement	No formal definitions	**Included**: 2nd strategy
Maintain	**23**	Preventive/corrective maintenance, lifetime extension, maintain value, clinical environment	**FDA/EMF/PBL/VH:** service, repair, retain product value	**Included**: 6th strategy
Repair	**22**	Recover functional obsolescence, extend product life, corrective maintenance	**FDA/ISO/UNEP/EMF/PBL/VH:** restore product to intended function	**Included**: 7th strategy
Remanufacture	**19**	Restore used equipment to "as new" or better condition, cleaning, renovation, quality control	**FDA/ISO/UNEP/EMF/PBL/VH:** industrial restoration to like-new condition	**Included**: 9th strategy
Rethink	**18**	Make systems/processes more environmentally sustainable, e.g., patient transport, purchasing, telemedicine, packaging; change beliefs/practices	**PBL:** increase product use intensity (sharing, multifunction)	**Included**: 3rd strategy
Renew	**17**	Renewable energy, biodegradable materials, remanufacturing	**ISO/EMF:** renewable energy/materials	**Included**: 12th strategy
Repurpose	**15**	Use discarded products for different purposes, contexts, locations; maximize product life	**ISO/PBL:** adapt product or parts for different function	**Included**: 10th strategy
Refurbish	**13**	Transform obsolete products to contemporary standards while maintaining intended use	**MDR/ISO/UNEP/EMF/PBL/VH:** restore functionality, quality, performance	**Included**: 8th strategy
Biodegrade	**11**	Biodegradable polymers, coatings, medications, energy recovery	**EMF:** natural breakdown into CO_2, water, biomass	**Grouped**: under renew
Refuse	**10**	Avoid unnecessary devices, procedures, consumption, disposal	**PBL:** make product redundant, abandon function or radically change product	**Included**: 1st strategy
Restore	**9**	Restore value, repair product/material, restore trust	None	**Grouped:** under repair
Closing loops	**9**	Develop value from waste, minimize waste, circular analogy	**ISO:** closed-loop system	**Excluded**: encompassed by other strategies
Research	**8**	Life cycle analyses, green device development, cost comparisons, renewable energy, lean & 6-sigma methods	None	**Excluded**: too broad
Retain	**5**	Retaining value, recycling, product use over time	None	**Partially grouped**: under maintain; remainder disregarded
Regenerate	**4**	Regenerative medicine, regenerating natural systems	**ISO/EMF:** improve/restore ecosystems, regenerative production	**Grouped**: under renew
Redistribute	**4**	Divert product to other customers or contexts	**EMF/VH:** enable reuse at high value	**Grouped**: under reuse/remanufacture
Share	**3**	Shared use of products or equipment	**EMF/VH:** multiple users sequentially, increase utilization	**Grouped**: under rethink
Resterilise	**2**	Sterilizing again for reuse	None	**Grouped**: under processes requiring sterilization
Slowing loops	**1**	Durable design, product longevity	None	**Excluded**: broad, overlapping
(Bio)remediate	**1**	Chemical recycling by microbial action; shared use (note: healthcare literature example included)	**EMF:** shared use; chemical recycling	**Grouped**: under renew

lacked clear standalone definitions, and were therefore scaled under other strategies or excluded as independent strategies.

While some strategies, such as *recycle*, are frequently mentioned in the literature, their priority in established CE frameworks (e.g., the 10R hierarchy, Butterfly Diagram) does not always align with frequency. To address this, the final *Circular Healthcare Flows visual* balances the frequency of terms in literature with framework-based prioritization. Strategies like *refuse* and *reduce* are positioned higher in the hierarchy to reflect sustainability impact and practical relevance, even if they are less frequently cited. This ensures that the taxonomy represents both evidence from literature and operational priorities in healthcare CE decision-making.

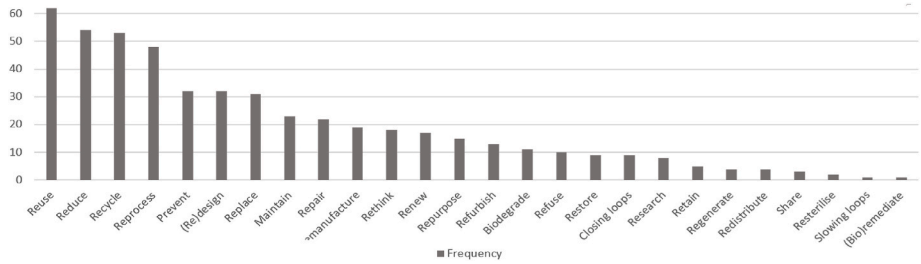

Fig. 3. Term mentioned by # of reviewed articles (n = 68).

3.4.1. Synonymous use of terms

The reviewed articles often indicated an overlap of definitions for the terms found, as shown in Table 4 and Fig. 4. Examples of citations labelled as synonymous use of terms are: "medical device reprocessing, or 'remanufacturing', refers to …" (McGain et al., 2020), "… and remanufactured (a.k.a. reprocessed) medical.

devices …" (Sherman et al., 2020), and "repair/refurbishment" (Kandasamy et al., 2022). For the terms not included in Table 4, no synonymous use was detected. For *reprocess* and *repair*, up to four alternative terms were used as synonyms. Notably, *reuse*, *remanufacture*, *repair*, and *recycle* were also used interchangeably with *reprocess*. Similarly, *repair* was described as synonym of *maintain*, *prevent*, and *refurbish,* and *retain* and *recover* were frequently used interchangeably. Additionally, some articles labelled specific terms as "R-strategies," including *reduce* (6 mentions), *research* (5), *rethink* (4), *reuse* (2), and *renew* (1).

3.4.2. Congruence with established definitions

Healthcare literature definitions were compared with previously established ones. No definitions were found for terms like *replace*, *restore*, *research*, *retain*, *resterilise*, *slowing loops*, and *(bio)remediate*. Terms with fewer than four occurrences or unclear definitions, like *closing loops* and *biodegrade*, were not compared. Among terms with multiple definitions, most shared key elements with established definitions but varied in emphasis or context. High congruence was found for *repair*, *recycling*, and *renew*, while *reuse* and *refurbish* were largely consistent, though healthcare-specific nuances exist. For example,

Table 4
Terms utilized as synonyms in healthcare literature, with darker squares representing where more synonymous use was found.

	Reuse	Reduce	Recycle	Reprocess	Prevent	(Re)design	Replace	Maintain	Repair	Recover	Remanufacture	Rethink	Renew	Refurbish	Refuse	Restore	Retain	Regenerate	(Bio)remediate
Reuse	NA	0	1	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reduce	0	NA	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Recycle	1	0	NA	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Reprocess	6	0	1	NA	0	0	0	0	1	1	2	0	0	0	0	0	0	0	0
Prevent	0	1	0	0	NA	0	0	2	1	0	0	0	0	0	1	0	0	0	0
(Re)design	0	0	0	0	0	NA	0	0	0	0	0	2	0	0	0	0	0	0	0
Replace	0	0	0	0	0	0	NA	0	0	0	0	0	0	0	1	0	0	0	0
Maintain	0	0	0	0	2	0	0	NA	6	0	0	0	0	0	0	0	0	0	0
Repair	0	0	0	1	1	0	0	6	NA	0	0	0	1	1	0	2	0	0	0
Recover	0	0	1	1	0	0	0	0	0	NA	0	0	0	1	0	2	5	0	0
Remanufacture	0	0	0	2	0	0	0	0	0	0	NA	0	1	3	0	0	0	0	0
Rethink	0	0	0	0	0	2	0	0	0	0	0	NA	0	0	2	0	0	0	0
Renew	0	0	0	0	0	0	0	0	1	0	1	0	NA	0	0	0	0	2	0
Refurbish	0	0	0	0	0	0	0	0	1	1	3	0	0	NA	0	0	0	0	0
Refuse	0	0	0	0	1	0	1	0	0	0	0	2	0	0	NA	0	0	0	0
Restore	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	NA	0	0	0
Retain	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	NA	0	0
Regenerate	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	NA	0
(Bio)remediate	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	NA

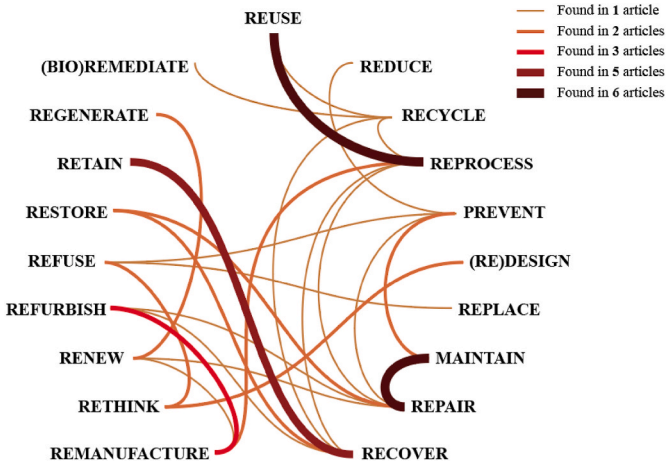

Fig. 4. Visualization of synonymous use of terms in healthcare literature.

healthcare *reuse* often refers to use of a device across multiple patients, where each patient counts as a separate reuse even if the same healthcare worker uses the device multiple times. In contrast, established CE definitions consider *reuse* as occurring only when a device is used by different users; multiple patients served by the same user typically count as a single reuse event. *Refurbish* definitions mostly align with established ones, except for the EU-MDR 2017/745 (MDR-EU, 2017, 2017) definition, which is closer to *remanufacturing*.

The term *recover* generally aligned well with established definitions, which focus on energy recovery or resource collection, rather than retaining products or product value. Terms with medium congruence included *reprocess*, *reduce*, *(re)design*, *prevent*, *maintain*, *remanufacture*, and *repurpose*. Established definitions for *reprocess* found in healthcare regulations (e.g. MDR-EU 2017/745 (MDR-EU, 2017, 2017) and FDA medical device regulation (Center for Devices and Radiological Health, 2020)) describe decontamination as a part of *reprocessing* but do not specifically address single-use devices, whereas healthcare literature does. Other terms, like *reduce* and *(re)design*, show healthcare-specific contextual differences. For instance, *(re)design* often includes decontamination considerations, and *prevent* encompasses infection and unnecessary procedures. *Remanufacturing* definitions were covered by established definitions despite variability in usage. *Repurpose* definitions vary in healthcare literature, describing changes in product function, context, or location, while established definitions focus solely on function changes.

Lastly, some terms showed low congruence among established definitions themselves. For example, in the Butterfly Diagram, *remanufacturing* can be interpreted as the re-engineering of products to an as-new condition (EllenMacArthur Foundationa), while in the 10R-strategies, *remanufacturing* refers to using parts of a discarded product in a new product (Potting et al., 2017), which the MDR-EU 2017/745 (MDR-EU, 2017, 2017) describes as *refurbishment*.

3.4.3. CE strategy process timeline and hierarchy

In addition to highlighting the divergence in the use of terms and definitions surrounding CE strategies in healthcare literature, the analysis provides insights for the visual taxonomy regarding timing and sequence of strategies. These details, however, exhibit notable variability across sources. For example, one article states that "*Reprocessing* is decontamination using disinfection or sterilization methods followed by *reuse*" (Toomey et al., 2021), suggesting that *reuse* follows *reprocess*, while other sources describe *reprocess* as including *reuse* or occurring as part of *recycle* and *remanufacture* processes. Similarly, *repair* is sometimes described as part of *refurbish*, *repurpose* as an enabler of *reuse*, *refurbish* as an enabler of *recover*, *redistribute* as part of *reuse* and/or *remanufacture*, and *recycle* as a method to *retain* value. Terms like closing loops and slowing loops are also mentioned in conjunction with other strategies, but their relationship to reuse and recycling varies across sources. Additionally, the hierarchy of strategies in CE frameworks does not always align with term frequency in literature. For example, the Value Hill (Achterberg et al., 2016) prioritizes *prevent*, while the 10R-strategies (Potting et al., 2017) emphasize *refuse* and *reduce*. While *prevent* and *reduce* occur frequently, *refuse*, the highest strategy on the 10-R hierarchy (Potting et al., 2017), does not. Conversely, *recycle*, a commonly used strategy term in literature, is considered a lower priority in frameworks such as the Butterfly Diagram (Ellen MacArthur Foundation, 2019).

3.5. Final visual taxonomy

Based on observational research, expert interviews, a systematic literature review, and expert stakeholder validations, the final visual taxonomy was developed (Fig. 5). A practical application of this visual taxonomy to a real-world healthcare device—the endoscope—is provided in Appendix H, demonstrating how the framework can guide circular economy decision-making across a device lifecycle. During content validation, the *Circular Healthcare Flows visual* iteration refined through the literature review (Appendix E) was validated and adjusted using expert feedback. For example, hospital sterilization staff refined decontamination steps, supply chain experts verified sequencing, and a designer integrated seven dimensions from the Collaborative Dimensions of Visualisations framework (Bresciani, 2019).

The taxonomy presents 13 healthcare-specific CE flows, each with steps and explanations. It introduces a standardized set of CE strategy definitions to reduce terminology inconsistencies in healthcare. These definitions are provided in Table 5, which aligns the strategies with established sustainability principles and incorporates healthcare-specific nuances. The visual depicts a linear economy supply chain (grey boxes) with 13 hierarchical flows connected by arrow loops. Each step includes explanations, likely stakeholders, expected transport needs, potential material leakage, and possible transitions between flows.

The process of developing the definitions in Table 5 is further explained in section 3.1.1. The table presents terms and definitions derived from literature, aligned with sustainability principles while reflecting healthcare-specific nuances. While the hierarchy is informed by the 10R-strategies, which prioritize sustainability actions based on impact and product integrity (Potting et al., 2017), it also reflects the timeline of processes in practice. In healthcare, maintenance and repair

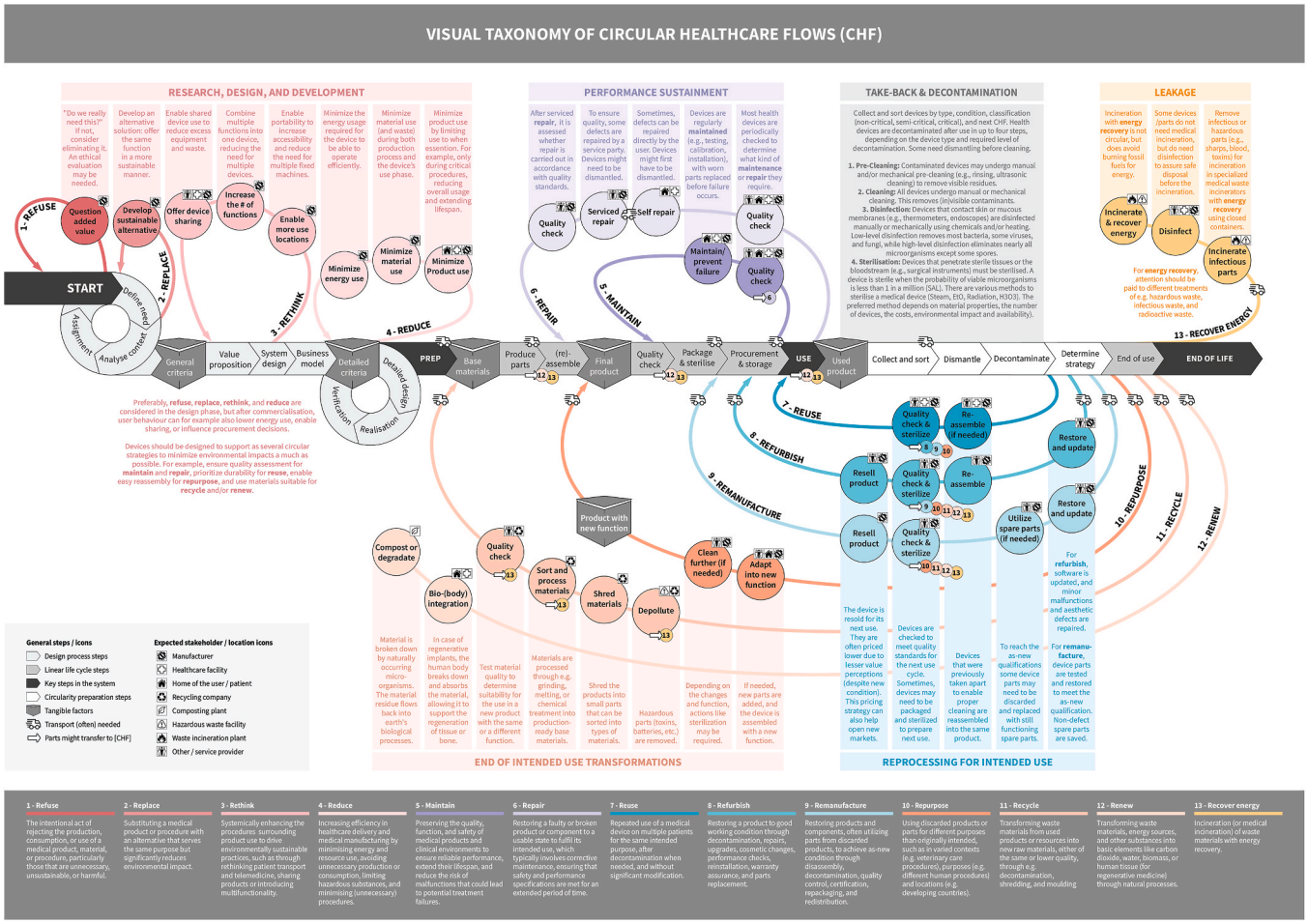

Fig. 5. Final *Circular Healthcare Flows visual*.

Table 5
Proposed healthcare-specific definitions for CE strategies.

	TERMS	HEALTHCARE-SPECIFIC DEFINITIONS
Reprocessing	**Refuse**	The intentional act of rejecting the production, consumption, or use of a medical product, material, or procedure, particularly those that are unnecessary, unsustainable, or harmful.
	Replace	Substituting a medical product or procedure with an alternative that serves the same purpose but significantly reduces environmental impact.
	Rethink	Systemically enhancing the procedures surrounding product use to drive environmentally sustainable practices, such as through rethinking patient transport and telemedicine, sharing products or introducing multifunctionality.
	Reduce	Increasing efficiency in healthcare delivery and medical product manufacturing by minimizing energy use, resources use and waste generation at the source, avoiding unnecessary production or consumption, limiting hazardous substances, and carefully minimizing (unnecessary) procedures to meet healthcare needs.
	Reuse	Repeated use of a medical device on multiple patients for the same intended purpose, after decontamination when needed, and without significant modification.
	Maintain	Preserving the quality, function, and safety of medical products and clinical environments to ensure reliable performance, extend their lifespan, and reduce the risk of malfunctions that could lead to potential treatment failures.
	Repair	Restoring a faulty or broken product or component to a useable state to fulfil its intended use, which typically involves corrective maintenance, ensuring that safety and performance specifications are met for an extended period of time.
	Refurbish	Restoring a product to good working condition through decontamination, repairs, upgrades, cosmetic changes, performance checks, reinstallation, warranty assurance, and parts replacement.
	Remanufacture	Restoring products and components, often utilizing parts from discarded products for the same function, to achieve as-new condition through disassembly, decontamination, quality control, certification, repackaging, and redistribution.
	Repurpose	Using discarded products or parts for different purposes than originally intended, such as in varied contexts (e.g. veterinary care procedures), purposes (e.g. different human procedures) and locations (e.g. developing countries).
	Recycle	Transforming waste materials from used products or resources into new raw materials, either of the same or lower quality, through e.g. decontamination, shredding, and moulding
	Renew	Transforming waste materials, energy sources, and other substances into basic elements like carbon dioxide, water, biomass, or human tissue (for regenerative medicine) through natural processes.
	Recover energy	Incineration (or medical incineration) of waste materials with energy recovery.

were placed higher than reuse because they often occur periodically during the use cycle rather than after use. Additionally, section 3.1.2 explains how insights from the collaborative dimensions framework (Bresciani, 2019) were integrated into the graphic design of the visual.

3.5.1. Development of healthcare-specific CE strategy definitions

To minimize confusion, several terms were not directly included in the list of definitions: *prevent*, *research*, *closing loops*, *slowing loops*, and *redistribute*. These terms were either too broad, overlapping with other strategies, or lacked a clear, standalone definition in the context of sustainability. For example, while preventive healthcare is essential for reducing environmental impact, the term *prevent* was deemed too broad to represent a single sustainable strategy, as it could also encompass preventing environmental damage and waste. Similarly, *(re)design* could apply to various contexts, such as redesigning a product for any strategy, replacing a product, or reducing energy consumption, making it too vague. *Research* and *redistribute* were also part of other strategies rather than being standalone. Finally, *closing loops* and *slowing loops* were excluded because they encompass multiple strategies.

To further improve comprehension of definitions in the visual taxonomy, terms with similar meanings were consolidated. For instance, based on the review analysis, part of *retain* was scaled under *maintain*, *share* under *rethink*, and *restore* under *repair*. All processes that referred to the *bio-cycle* as described by EMF (EllenMacArthur Foundation, 2022) (*renew*, *biodegrade*, *regenerate*, and *(bio)remediate*), were scaled under *renew*.

Despite its frequent use in healthcare literature, *reprocess* has significant divergence in its meaning. Likely derived from *processing*, as defined in ISO 17664:2021 (preparing new or used healthcare products for intended use), *reprocessing* typically refers to preparing used products after the use cycle for the same purpose in a next use cycle. This includes processes like *reuse*, *refurbish*, and *remanufacture* but not *maintain* and *repair* (as those take place during the use cycle), or *repurpose* and *recycle* (as those will not result in a product used for the same purpose). This aligns with established definitions and review findings, where decontamination is emphasized in healthcare but is not the only step. Due to its widespread use, *reprocess* was included as an overarching term in the framework. More specific subcategories are recommended to reduce terminology confusion and foster interdisciplinary collaboration.

3.5.2. Improvement of visual communication

The *Circular Healthcare Flows visual* was optimized for utilization in multidisciplinary collaboration following the different dimensions of the Collaborative Dimensions of Visualisations framework (Bresciani, 2019). Table 6 explains the meaning of each dimension and how it was adopted into the design of the visual taxonomy.

4. Discussion

While circular economy (CE) strategies are increasingly discussed in the healthcare sector, existing models—such as the Butterfly Diagram (Ellen MacArthur Foundation, 2019)—often lack the specificity needed for contexts with strict regulatory and operational constraints. This, together with inconsistent use of terms like *reuse*, *reprocess*, *refurbish*, and *remanufacture*, creates confusion and can hinder effective implementation. To address this challenge, this paper aimed to provide conceptual clarity by harmonizing terminology in healthcare contexts. It introduced the *Circular Healthcare Flows visual taxonomy*: an operationalization of CE frameworks that categorizes strategies for the physical flow of products and materials in healthcare.

Observational research, stakeholder interviews, bibliometric analysis, and literature review each informed the *Circular Healthcare Flows visual*. Observations in hospitals and production sites uncovered healthcare-specific process nuances, such as sterilization steps and material handling, which guided the inclusion of key workflow elements in the visual. Expert interviews highlighted inconsistencies in terminology and practical usability challenges, shaping updates to definitions, labelling, and visual layout. Insights from the bibliometric analysis helped clarify relationships between CE terms and highlighted sector-specific interpretations in healthcare literature. The systematic literature review enabled standardization of definitions and alignment with established CE hierarchies. By linking these insights with the other data sources, the taxonomy was iteratively refined to be conceptually clear,

Table 6
Design Integration of Collaborative Dimensions Framework (based on Bresciani et al. (Bresciani, 2019)).

Dimension	Original definition	Contextual Translation	Application in Visual
Structural restrictiveness	Extent to which the design process is guided or constrained by the visualization.	Visual design should enable healthcare professionals and stakeholders, including medical device developers, to uncover new insights about interconnections and potential process optimizations within the circular economy framework, specifically highlighting hierarchical flows and critical CE steps in healthcare contexts.	Integrated visual cues, such as hierarchical, iterative arrow loops and transition icons, encourage users to draw conclusions about possible systemic steps and process enhancements, effectively bridging theory and practical implications.
Content modifiability	Extent to which the items of a visualization can be dynamically changed.	Visual is intentionally designed with low modifiability to ensure consistency, reliability, and standardization in healthcare CE discussions. It is a fixed reference that cannot be altered by individual users. Instead, users can customize which steps are relevant to the device being considered, but the overall structure remains unchanged.	The visual is a structured, validated reference that prevents ad-hoc modifications while still allowing periodic expert-driven updates. This ensures users rely on a stable framework for decision-making rather than making individual, unverified alterations.
Directed focus	Extent to which the main item(s) of the discussion is visually emphasized.	Visual should highlight the most critical elements of the CE strategies—such as key decision nodes that determine circularity success—to guide stakeholder focus during discussions. Emphasis is placed on post-use decision points relevant to both healthcare workflows and medical device lifecycle decisions.	Strategic use of contrasting colours and focal markers (for instance, accentuating the start of the timeline) directs attention to essential steps and facilitates focused dialogue on process improvements.
Perceived finishedness	Extent to which visual cues suggest whether an object appears finished.	Visual must appear professionally refined (and thus "finished") to build trust among healthcare stakeholders, reflecting the rigorous validation by hospital, MedTech, and design experts. A polished appearance reassures clinical, administrative, and device development audiences of reliability.	The visual design is highly refined, with consistent use of design elements such as colour, font, and layout. There are no unfinished sketches or ambiguous elements. The design appears as a finished, standardized product that inspires confidence.
Outcome clarity	Extent to which a visual representation is self-explanatory and easily understandable with low cognitive effort.	Visual should be clear and intuitive, providing a straightforward representation of the CE process for medical devices with minimal explanation required. Healthcare staff and medical device developers can quickly interpret processes and decision points without specialized CE training.	Simple icons, colour coding, and a logical flow from one step to the next help viewers quickly understand the CE process without confusion. Minimal attention is drawn to the explanatory texts and clear labelling is used to ensure ease of understanding.
Visual appeal	Extent to which a visual representation is attractive and pleasant to the eyes.	Visual must be visually compelling to effectively engage stakeholders and support their understanding of CE processes for medical devices. This includes clear, intuitive layout and colour coding for different flows.	Iconography (e.g., for stakeholder location and need for transportation) is used alongside dynamic arrow loops connecting 13 flows, ensuring key messages are memorable.
Collaboration support	Extent of the control over the flow of the group discussion which is exercised by a visualization.	Visual should facilitate structured discussions among healthcare stakeholders by providing a shared reference point for decision-making. Supports interdisciplinary alignment in hospital, MedTech, and device development CE initiatives.	The standardized visual ensures consistent terminology and process clarity, reducing misinterpretation. Its structured layout guides CE discussions without the need for modifications, using icons and color-coded segments to highlight key stages for easy reference.

practically useable, and tailored to the specific regulatory, clinical, and operational requirements of healthcare. The results highlighted confusion between the terms. For example, in interviews and healthcare literature, terms like *reprocess* were often used interchangeably with *reuse*, *repair*, and *remanufacture*, despite representing distinct processes in established sustainability frameworks. Additionally, the bibliometric analysis highlighted inconsistencies in how CE terms are used across healthcare literature, further supporting the need for a standardized set of definitions. These observed inconsistencies directly guided the categorization and definition of terms in the *Circular Healthcare Flows visual*, ensuring that the taxonomy reflects both conceptual clarity and practical applicability. For example, the taxonomy treats *reprocessing* as an overarching category encompassing *reuse*, *repair*, *refurbish*, and *remanufacture*, while remaining distinct from processes like *repurpose* or *recycle*.

The final visual taxonomy builds on and refines existing CE frameworks, including the Butterfly Diagram (Ellen MacArthur Foundation, 2019), 10R framework (Potting et al., 2017), Value Hill model (Achterberg et al., 2016), and UNEP's Re-defining Value report (United Nations Environment Programme and International Resource Panel, 2018). It extends these frameworks by adapting their CE strategies to healthcare, clarifying terminology, and mapping flows to reflect operational, clinical, and regulatory considerations. This underscores that CE strategies cannot be applied uniformly across sectors but must be adapted to incorporate sector-specific processes and requirements to balance circularity with safety and compliance. Additionally, although hierarchical models like the 10R framework (Potting et al., 2017) or Butterfly Diagram (Ellen MacArthur Foundation, 2019) suggest higher-order strategies such as *refuse* or *rethink* are always preferable, previous work (Hoveling et al., 2024b) shows they do not consistently achieve lower environmental impacts than downstream options like *repair* or *remanufacture*. Therefore, while the *Circular Healthcare Flows visual* does present a hierarchy to organize strategies conceptually, it is not intended as a strict ranking of environment or operational benefit. Rather, it supports context-sensitive decision-making based on operational, clinical, and regulatory factors.

Beyond its conceptual value, the *Circular Healthcare Flows visual* has the potential to hold practical contributions, depending on the taxonomy being widely accepted and adopted. For medical device designers, it offers a structured approach to integrate circularity principles early in the design process, ensuring that products are circularly designed from the outset. Hospital procurement teams can use it to distinguish between suppliers offering *reuse*, *refurbishment*, or *remanufacturing* services, reducing ambiguity and aiding regulatory compliance. Clinical staff, such as nurses and sterile services technicians, gain a clearer understanding of *reprocessing* responsibilities and steps, helping to standardize practices and ensure patient safety. Remanufacturers and third-party reprocessors can better align quality control documentation and compliance protocols with clearly defined categories, ensuring consistency across the sector. Policymakers and regulators can leverage the taxonomy to develop clearer, more targeted guidelines and regulations, reducing uncertainty around the application of CE strategies in healthcare. Finally, it can help facilitate collaboration between all these disciplines by helping create a common language.

By combining conceptual structure with practical guidance, the *Circular Healthcare Flows visual* connects theory and practice, addressing infection control, material flows, the roles of diverse stakeholders, and regulatory requirements in healthcare.

4.1. Limitations

While this study develops and validates a visual taxonomy framework for circular economy (CE) strategies in healthcare, several limitations should be acknowledged. The analysis primarily relied on literature synthesis and expert input, which, although valuable, may not fully capture real-world complexities. Feedback from healthcare professionals, policymakers, and sustainability experts enhanced the framework's robustness, yet its transferability across different healthcare systems requires further empirical validation. Therefore, the described use cases represent projected applications based on expert input rather than empirically tested outcomes. The review was limited to English-language sources, potentially excluding relevant insights. Moreover, the initial search strategy may have shaped the concepts identified; future studies could broaden these parameters and assess the framework across diverse contexts.

The study also does not fully account for contextual barriers to CE implementation, particularly in settings with limited infrastructure, resource constraints, or unclear regulatory environments. Restricted access to clean technologies and institutional capacity may further constrain adoption and scalability. In addition, behavioural and organizational dynamics—such as procurement practices, staff training needs, and resistance to reuse—pose further challenges to circular implementation. Addressing these structural, institutional, and behavioural barriers is essential for translating CE strategies into practical, context-sensitive solutions within healthcare.

4.2. Future research

Future research could focus on validating the framework through real-world applications and expanded stakeholder engagement. Delphi panels are particularly suitable for this purpose, as they enable structured consensus-building among diverse expert stakeholders across healthcare, regulatory, and design domains (Mahajan, 1976; Linstone and Turoff, 1975). Building on this foundation, the framework is intended to serve as the conceptual backbone for developing a Circular Design Guide for healthcare, supporting decision-making on sustainable procurement, asset management, and waste reduction. Future studies should include pilot implementation studies in hospital procurement, device lifecycle management, and clinical workflows to empirically evaluate the usability, adoption, and operational impact of the taxonomy. This guide could be integrated into decision-support systems, such as public procurement guidelines, hospital management software, or regulatory assessment frameworks, to enable actionable implementation of circular strategies. Future studies should therefore explore pathways for such integration and evaluate the usability, policy relevance, and operational impact of these tools in diverse healthcare settings. Empirical research should also assess how adoption of the framework influences collaboration, decision-making, and compliance with circular economy objectives across healthcare systems. Additionally, the potential of the *Circular Healthcare Flows visual* as an educational and training tool could be explored, helping staff across clinical, operational, and administrative roles to understand and apply circular economy strategies in daily practice.

5. Conclusion

This study addresses an important gap in healthcare: the confusion created by inconsistent and conflicting terminology around circular economy (CE) strategies. It proposes a sector-specific visual taxonomy to standardize CE terminology for healthcare. Grounded in a systematic review, expert interviews, and observational research, it clarifies terms such as *reuse*, *repair*, *reprocess*, *remanufacture*, and *refurbish* to improve communication and decision-making. Inspired by broader frameworks such as the Butterfly Diagram or 10R model, this taxonomy translates CE principles into a healthcare-specific framework that reflects regulatory and clinical considerations. It supports policy development, practical implementation, and stakeholder awareness, enabling consistent integration of circularity into design, procurement, and use. Ultimately, if widely adopted in practice, it provides a foundation for measurable and scalable implementation of circular economy strategies across global healthcare systems.

CRediT authorship contribution statement

Tamara Hoveling: Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jelle Ijzenbrandt:** Writing – review & editing, Investigation. **Saba Hinrichs-Krapels:** Writing – review & editing, Methodology, Formal analysis. **Linda Ritzen:** Writing – review & editing, Validation, Investigation. **Wichor M. Bramer:** Writing – review & editing, Formal analysis. **Erik van Raaij:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Jeremy Faludi:** Writing – review & editing, Visualization, Supervision. **Conny Bakker:** Writing – review & editing, Visualization, Supervision. **Jan-Carel Diehl:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of generative ai in the manuscript preparation process

During the preparation of this work, the author(s) used **ChatGPT (OpenAI)** to find appropriate phrasing and improve clarity. After using this tool, the author(s) thoroughly reviewed and edited the content and take full responsibility for the scientific content and accuracy of the published article.

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Declaration of competing interest

The authors 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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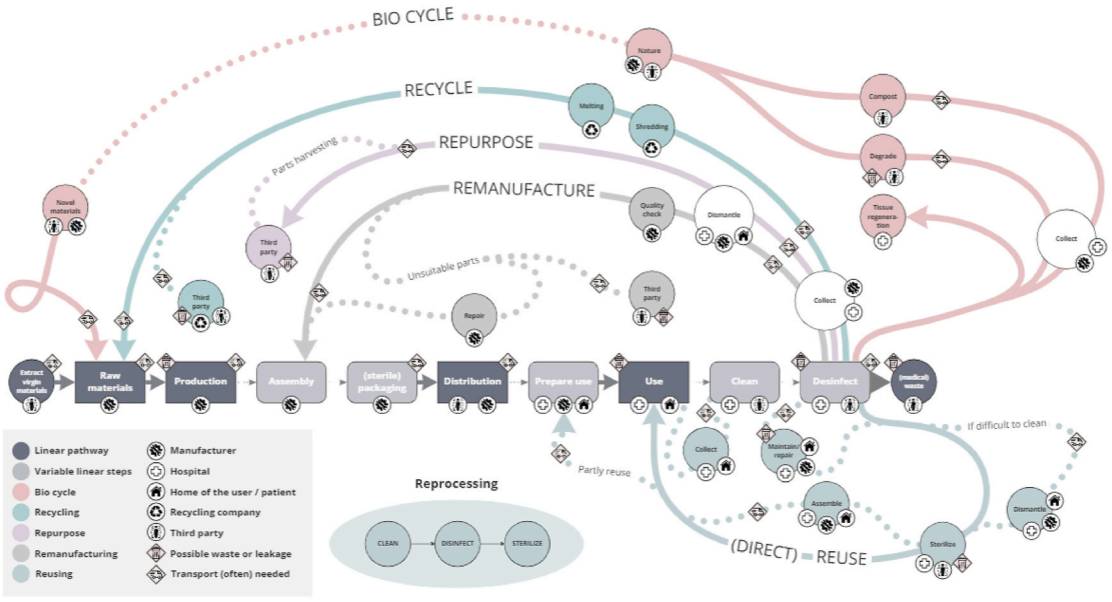
We thank all consulted experts and stakeholders for providing valuable feedback throughout the research process. We also appreciate the partners from the DiCE consortium for reviewing drafts of the manuscript and contributing their insights.

APPENDIX A. Initial visual - research probe for interviews



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APPENDIX B. Expert Interviews protocol

Below, the interview protocol used during all expert interviews of the second interview cycle is displayed. Note that the protocol below does only include the content-specific questions, and not the introduction.

First, explain to the participant: *we are developing a visual that displays the different processes that (medical) product can go through after use to make then circular. We are assuming that you have some experience in* [specific process(es) of their expected expertise]*, because* […]*. If you also have other knowledge that might be relevant to answer our research questions, please let us know. We will show you the visual with all the steps.*

[show the visual to the participant while explaining it in detail]

Question 1: How would you define the terms displayed in this visual (e.g. recycling, remanufacturing, reprocessing, reuse, repurpose)? Do you believe we have used the terms correctly in our visual? We will use the by-you preferred terms in the continuation of this interview.

Question 2: The image displays that health devices will be collected after disinfection and will then be processed in different kinds of ways to loop back into a production process or into nature. We want to know what is correct or incorrect about this overview, so we can adjust it until it is accurate.

[Go through the visual in detail again, asking for feedback on each detail of their expertise. Let the participant specify what they like about the current visual and what they think should be improved. In case participants are struggling to provide points of improvement, follow-up questions below are example questions that can be used to ask for further clarification where needed.]

Question 2.1: What do you think are the most important differences between [flow] and [flow]?

Question 2.2: Collection and sorting were already proven to be a huge barrier to circularity in healthcare. Do you agree?

Question 2.3: Do you think that we should elaborate more on the exact collection processes in our visual? If yes, can you provide us with detailed steps?

Question 2.4: How do you think should be dealt with the dangers of electronics?

Question 2.5: How do you think should be dealt deal with the dangers of medical waste?

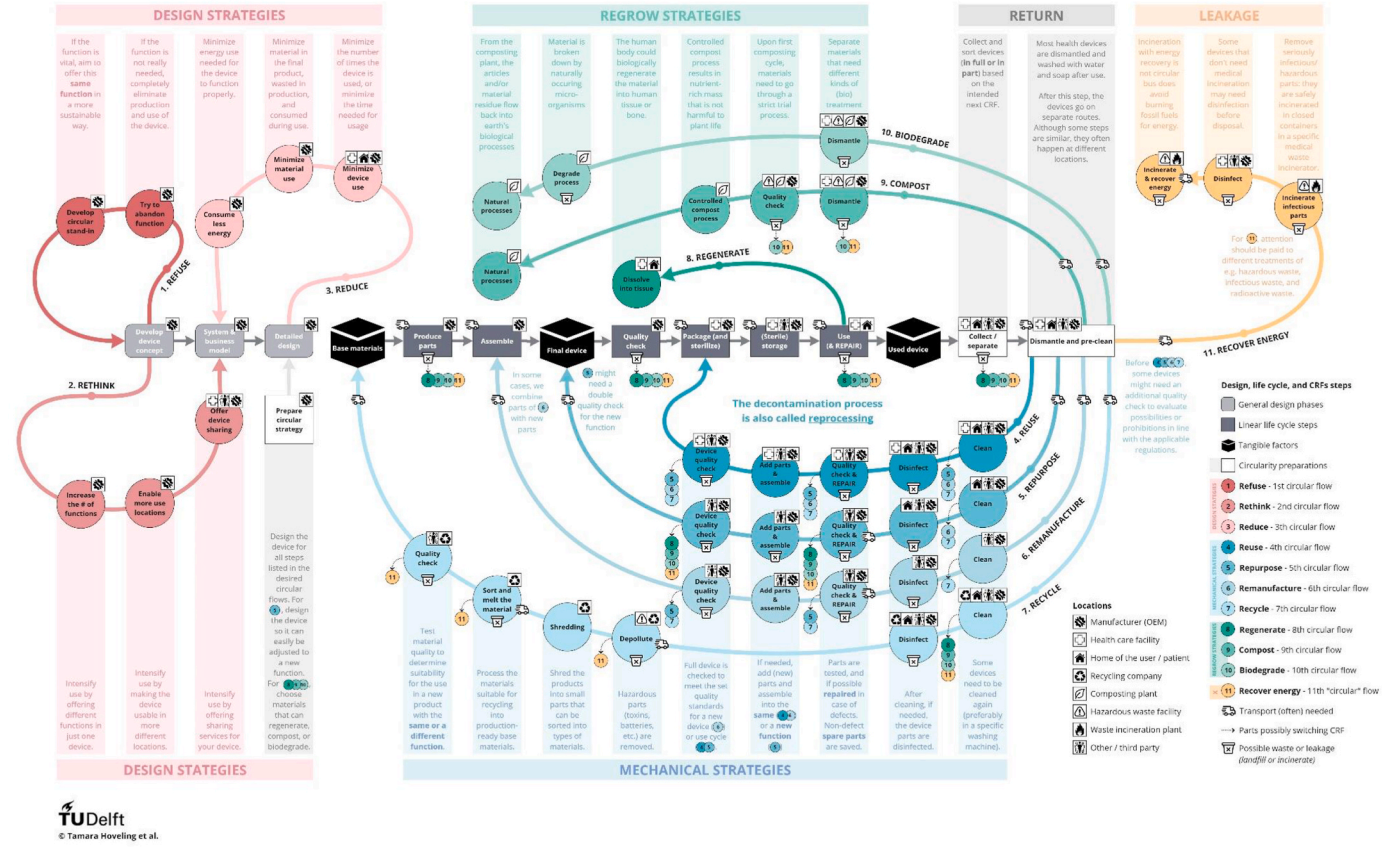
Question 2.6: How do you know which materials you are dealing with and how to handle them?

Question 2.7: How do devices or components reach the right facilities?

Question 2.8: What are the procedures in place for devices that need to be disassembled or sorted with a specific waste stream, such as highly infected devices?

Question 2.9: Can you provide us with some examples of [flow of expertise] systems in healthcare that were successful? Why do you think those work well?

APPENDIX C. UPDATED VISUAL AFTER EXPERT INTERVIEWS



APPENDIX D. FULL SEARCH STRINGS

The following sections present the complete search strings used in search phase one and phase two, exemplified for the Medline search.

Table 7
Search Strategies Phase 1

Database searched	Platform	Years of coverage	Records	Records after duplicates removed
Medline ALL	Ovid	1946 - Present	1685	1678
Embase	Embase.com	1971 - Present	2523	1569
Web of Science Core Collection*	Web of Knowledge	1975 - Present	532	180
Total			**4740**	**3427**

Medline Search String Search Phase 1

(* Equipment Reuse/OR * Recycling/OR ((* Surgical Equipment/OR * Disposable Equipment/OR exp * "Equipment and Supplies"/OR * Equipment Design/) AND (* Sustainable Development/OR * Carbon Footprint/OR * Waste Management/OR * Refuse Disposal/OR * Medical Waste Disposal/OR * Environment/)) OR (circularit* OR ((repair* OR reuse* OR reusab* OR redistribut* OR restoration* OR recondition* OR regenerat* OR recover* OR refurbish* OR recontextuali* OR reprocess* OR recycl* OR sustainab* OR closed-loop* OR carbon-footprint* OR downcycl* OR upcycl* OR Resterili* OR multi-use OR repurpos* OR waste-collection* OR waste-separation* OR waste-management* OR environmental*-friend*) ADJ6 (device* OR resource* OR equipment* OR material* OR medical-product* OR instrument*)) OR green-team*).ti.) AND (exp * Drug Therapy/OR exp * Delivery of Health Care/OR exp * Hospitals/OR exp * Surgical Procedures, Operative/OR diagnostic procedure/OR ((drug* ADJ3 therap*) OR pharmaceutic* OR health-care* OR healthcare* OR hospital* OR medical* OR surger* OR surgical* OR diagnos* OR rehabilitation* OR intensive-care OR icu OR (operating ADJ (room* OR theat*))).ti.) NOT (* DNA repair/OR (((surgical* OR dna OR tissue OR wound) ADJ3 repair*) OR repair-device*).ti.) NOT (news OR congres* OR abstract* OR book* OR chapter* OR dissertation abstract*).pt.

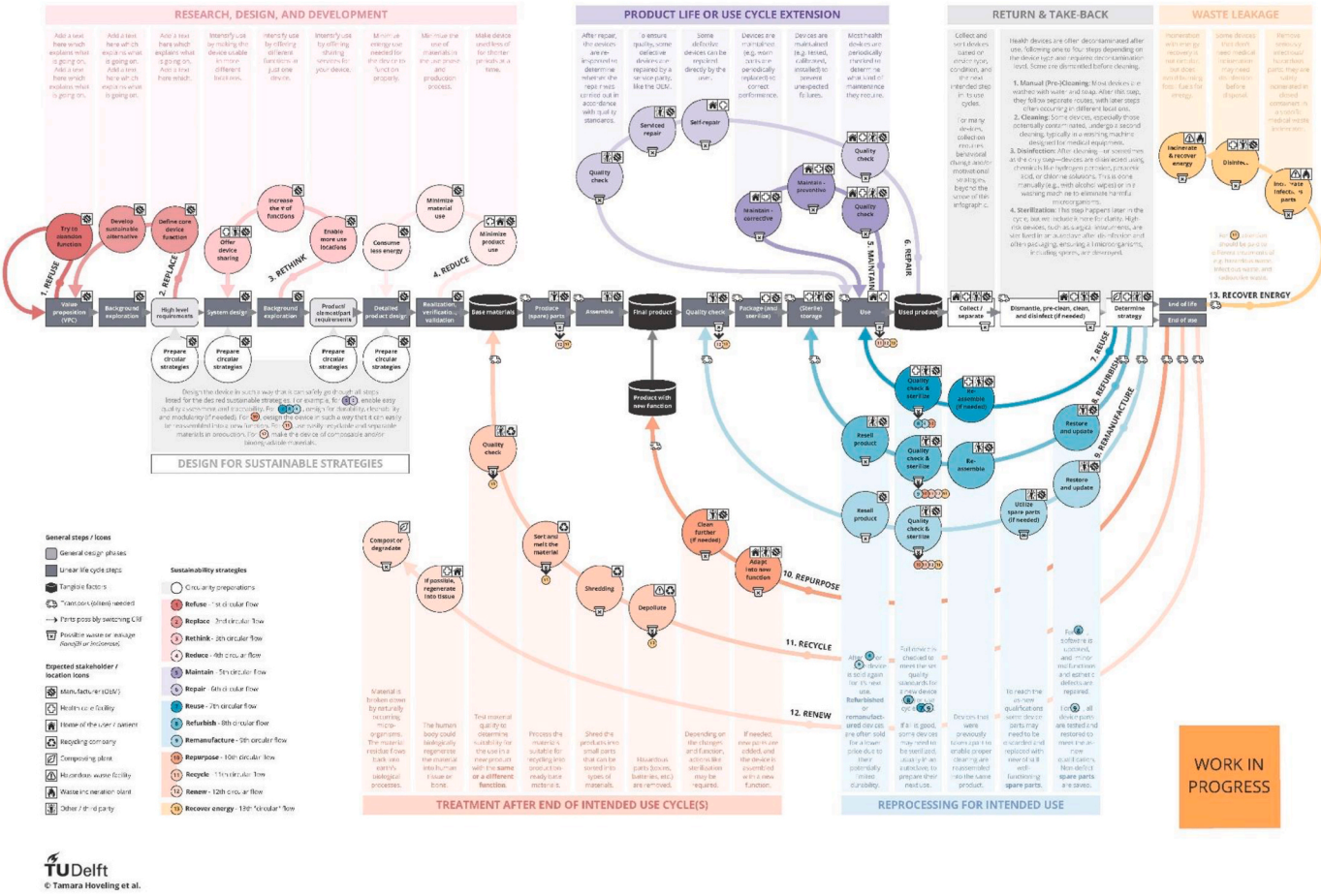
Table 8
Search Strategies Phase 2

Database searched	Platform	Years of coverage	Records	Records after duplicates removed
Medline ALL	Ovid	1946 - Present	284	283
Embase	Embase.com	1971 - Present	547	412
Web of Science Core Collection*	Web of Knowledge	1975 - Present	98	38
Total			**929**	**733**

Medline Search String Search Phase 2

(* Equipment Reuse/OR * Recycling/OR ((* Surgical Equipment/OR * Disposable Equipment/OR exp * "Equipment and Supplies"/OR * Equipment Design/) AND (* Sustainable Development/OR * Carbon Footprint/OR * Waste Management/OR * Refuse Disposal/OR * Medical Waste Disposal/OR * Environment/)) OR (circularit* OR (circular* ADJ3 (econom* OR material* OR product*)) OR ((repair* OR reuse* OR reusab* OR recondition* OR regenerat* OR recover* OR refurbish* OR recontextuali* OR reprocess* OR recycl* OR sustainab* OR closed-loop* OR carbon-footprint* OR downcycl* OR upcycl* OR Resterili* OR multi-use OR repurpos* OR waste-collection* OR waste-separation* OR waste-management* OR environmental*-friend*) ADJ6 (device* OR resource* OR Consumable* OR Packaging* OR Disposable* OR equipment* OR material* OR medical-product* OR instrument*)) OR green-team* OR (environment* ADJ3 sustainab*)).ti.) AND (exp * Drug Therapy/OR exp * Delivery of Health Care/OR exp * Hospitals/OR exp * Surgical Procedures, Operative/OR * diagnostic procedure/OR ((drug* ADJ3 therap*) OR pharmaceutic* OR health-care* OR healthcare* OR hospital OR hospitals OR medical* OR surger* OR dentist* OR surgical* OR diagnos* OR rehabilitation* OR intensive-care OR icu OR (operating ADJ (room* OR theat*)) OR medical*).ti.) NOT (* DNA Repair/OR (((surgical* OR dna OR tissue OR wound) ADJ3 repair*) OR repair-device*).ti.) NOT (news OR congres* OR abstract* OR book* OR chapter* OR dissertation abstract*).pt. AND (Review/OR Systematic Review/OR Meta-Analysis/OR (review* OR meta-analy*).ti. OR (((literature* OR systematic* OR scoping OR comprehensive*) ADJ3 (review)) OR ((pubmed OR medline OR embase) AND (review))).ab,ti,kw.)

APPENDIX E. Updated visual after systematic literature review



APPENDIX F. Included/excluded review articles

In this appendix, we present two tables: one with all articles that were excluded during the full-text review stage and the main reasons for exclusion (as presented in the PRIMA diagram) (Table 9), and one representing a simplified version of our extraction table, displaying all included articles and which terms which were mentioned in which articles, including the degree to which the articles provided definitions for those terms (Table 10).

Table 9
Main reasons for article exclusion in full text review stage

TITLE	AUTHORS	PUB. DATE	MAIN REASON FOR EXCLUSION
Healthcare Environmental Footprint: Proposal to Deliver Sustainability through an Innovative Value Stream Using a Circular Economy Approach	Leiva, W.	1-7-2023	Not a scientific literature review
Healthcare Waste and Sustainability: Implications for a Circular Economy	Mahjoob, A.; Alfadhli, Y.; and Omachonu, V.	1-5-2023	Not a scientific literature review
Environmentally Sustainable Endoscopy Practices	Jain, M.	1-1-2023	Not a scientific literature review
Reusable personal protective equipment in Canadian healthcare: Safe, secure, and sustainable	Varangu, L.; Cowan, K.; Amin, O.; Sarrazin, M.; Dawson, M.; Rubinstein, E.; Miller, F. A.; Hirst, L.; Trbovich, P.; Waddington, K.	1-7-2023	Not a scientific literature review
Technical evaluation of steam sterilization coupled with gasification to improve circularity of Australian hospital waste management: A case study	Harris, P.; McCabe, B. K.	1-1-2024	Not a scientific literature review
Environmental Sustainability and MRI: Challenges, Opportunities, and a Call for Action	Chaban, Y. V.; Vosshenrich, J.; McKee, H.; Gunasekaran, S.; Brown, M. J.; Atalay, M. K.; Heye, T.; Markl, M.; Woolen, S. A.; Simonetti, O. P.; Hanneman, K.	1-1-2024	Not a scientific literature review
How to choose between single-use and reusable medical materials for sustainable nursing: Methodological lessons learned from a national study	Vanderwee, K.; Demarre, L.; Malfait, S.; Kieckens, E.; De Waegemaeker, P.; Duprez, V.; Fraeyman, N.	29-5-2024	Not a scientific literature review
Environmentally sustainable kidney care through transplantation: Current status and future challenges	Anastasopoulos, N. A.; Papalois, V.	1-8-2024	Not a scientific literature review
Regulatory landscape, risks, and solutions for refurbished medical devices: a comparative analysis in the US, EU, Malaysia, and Ghana	Pinheiro, A. M.; Chettri, B.; Mehra, A.; Deepti, I.; Ravi, R.;	11-8-2024	Not a scientific literature review
Reusable instruments are more cost-effective than disposable instruments for laparoscopic cholecystectomy	Apelgren, K. N.; Blank, M. L.; Slomski, C. A.; Hadjis, N. S.	1-1-1994	Not a scientific literature review
Special problems associated with reprocessing instruments in outpatient care facilities: Physical spaces, education, infection preventionists, industry, reflections	Bringhurst, J.	1-1-2019	Not a scientific literature review
Reducing Disposable Surgical Items: Decreasing Environmental Impact and Costs at a Children's Hospital	Cunningham, A. J.; Krishnaswami, S.; Schofield, C.; Kenron, D.	1-1-2020	Not a scientific literature review
Reuse of disposable laparoscopic instruments: cost analysis	DesCoteaux, J. G.; Poulin, E. C.; Lortie, M.; Murray, G.; Gingras, S.	1-12-1995	Not a scientific literature review
Health service planning and sustainable development: considering what, where and how care is delivered through a pro-environmental lens	Desmond, S.	1-1-2018	Not a scientific literature review
Sustainability in Dentistry: A Multifaceted Approach Needed	Duane, B.; Stancliffe, R.; Miller, F. A.; Sherman, J.; Pasdeki-Clewer, E.	1-1-2020	Not a scientific literature review
Microbiological monitoring of endoscopes: 5-year review	Gillespie, E. E.; Kotsanas, D.; Stuart, R. L.	30-10-2007	Not a scientific literature review
Standards of Infection Prevention in Reprocessing Flexible Gastrointestinal Endoscopes	Herrin, A.; Loyola, M.; Bocian, S.; Diskey, A.; Friis, C. M.; Herron-Rice, L.; Juan, M. R.; Schmelzer, M.; Selking, S.	1-9-2016	Not a scientific literature review
Products liability implications of reprocessing and reuse of single-use medical devices	Hogan, J. M.; Colonna, T. E.	1-1-1998	Not a scientific literature review
Becoming environmentally sustainable in healthcare: an overview	Jamieson, M.; Wicks, A.; Boulding, T.	1-9-2015	Not a scientific literature review
A technique for re-utilizing catheter insertion sites in children with difficult central venous access	Johnson, S. M.; Garnett, G. M.; Woo, R. K.	1-1-2017	Not a scientific literature review
Managing environmental sustainability in a healthcare setting	Langstaff, K.; Brzozowski, V.	1-3-2017	Not a scientific literature review
The nurse's role on green teams: an environmental health opportunity	McDermott-Levy, R.	1-3-2011	Not a scientific literature review
The role of biofilms in reprocessing medical devices	Roberts, C. G.	1-5-2013	Not a scientific literature review
Creating an Environmentally Sustainable Neonatal Intensive Care Unit	Shepley, M. M.; Song, Y. L.; Marshall-Baker, A.	1-12-2016	Not a scientific literature review
Assessing the challenges to medical waste management during the COVID-19 pandemic: Implications for the environmental sustainability in the emerging economies	Tushar, S. R.; Alam, M. F. B.; Bari, Abmm; Karmaker, C. L.	18-1-2023	Not a scientific literature review
Reprocessing Single-Use Devices in the Ambulatory Surgery Environment	Ubaldi, K.	4-2-2019	Not a scientific literature review
Modelling the factors in implementation of environmental sustainability in healthcare organizations	Vaishnavi, V.; Suresh, M.	1-1-2023	Not a scientific literature review
Key considerations on the development of biodegradable biomaterials for clinical translation of medical devices: With cartilage repair products as an example	Wang, L.; Guo, X.; Chen, J.; Zhen, Z.; Cao, B.; Wan, W.; Dou, Y.; Pan, H.; Xu, F.; Zhang, Z.; Wang, J.; Li, D.; Guo, Q.; Jiang, Q.; Du, Y.; Yu, J.; Heng, B. C.; Han, Q.; Ge, Z.	1-3-2022	Not a scientific literature review

(continued on next page)

Table 9 (*continued*)

TITLE	AUTHORS	PUB. DATE	MAIN REASON FOR EXCLUSION
Reuser friendly: a review of the regulation of and the product liability regarding the reuse of single-use medical devices	Wood, J. M.; Heyman, G. F.	1-1-2001	Not a scientific literature review
Climate Change and the Professional Obligation to Socialize Physicians and Trainees into an Environmentally Sustainable Medical Culture	Wortzel, J. R.; Guerrero, A. P. S.; Aggarwal, R.; Coverdale, J.; Brenner, A. M.	10-2-2022	Not a scientific literature review
Environmental sustainability and the carbon emissions of pharmaceuticals	Richie, C.	5-2-2022	Not related to healthcare
Affecting medical equipment maintenance management: A systematic review	Bahreini, R.; Doshmangir, L.; Imani, A.;	1-1-2018	Not related to environmental sustainability
Assessment of medical equipment maintenance management: proposed checklist using Iranian experience	Arab-Zozani, M.; Imani, A.; Doshmangir, L.; Dalal, K.; Bahreini, R.;	1-1-2021	Not related to environmental sustainability
Sustainable equipment donation in otolaryngology in low-resource settings	De Cates, C.; Guéroult, A. M.; Narantsolmon, G. E.	1-1-2024	Not related to environmental sustainability
Recent advances on sustainable cellulosic materials for pharmaceutical carrier applications	Yan, G.; Chen, B.; Zeng, X.; Sun, Y.; Tang, X.; Lin, L.	15-9-2020	Not related to environmental sustainability
Reprocessing single-use medical devices	Cohoon, B. D	1-3-2002	Not related to environmental sustainability
Biocatalytic remediation of pharmaceutically active micropollutants for environmental sustainability	Bilal, M.; Lam, S. S.; Iqbal, H. M. N.	15-1-2022	Not related to materials, devices, consumables, equipment, or products
Environmental sustainability in the intensive care unit: challenges and solutions	Huffling, K.; Schenk, E.	1-7-2014	Not related to materials, devices, consumables, equipment, or products

Table 10
Simplified version of extraction table

TITLE	AUTHORS	PUB. DATE	TERMS FOUND (0 = not mentioned, 1 = not defined, 2 = clear in-context definition, 3 = clearly defined)																									
			Replace	*Recycle*	*Reduce*	*Reuse*	*Maintain*	*Repair*	*Restore*	*Repurpose*	*Rethink*	*Reprocessing*	*Refuse*	*Retain*	*Refurbish*	*Research*	*Redistribution*	*Recover*	*Remanufacture*	*(re)design*	*Slowing loops*	*Closing loops*	*Biodegrade*	*Renew*	*Share*	*Regenerate*	*Resterilise*	*(bio)remediate*	*Prevent*
Implementation approaches to improve environmental sustainability in operating theatres: a systematic review	Davies, J. F.; Ikin, B.; Francis, J. J.; McGain, F.	20-6-2023	1	1	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Sustainable practices in hospital and operating theatres	Anract, J.; Pradere, B.; Pinar, U.	1-9-2024	0	1	3	2	2	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Environmentally sustainable gastroenterology practice: Review of current state and future goals	Sonaiya, S.; Marino, R.; Agollari, K.; Sharma, P.; Desai, M.	1-4-2024	3	1	3	2	0	0	0	0	1	2	0	0	0	1	0	0	0	2	0	0	0	1	0	0	0	0	3
A systematic review comparing the safety, cost and carbon footprint of disposable and reusable laparoscopic devices	Chauvet, P.; Enguix, A.; Sautou, V.; Slim, K.	1-4-2024	3	0	3	2	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	3
Improving environmental sustainability of intensive care units: A mini-review	See, K. C.	9-9-2023	3	1	3	2	0	2	0	0	0	3	0	0	0	0	0	2	0	3	0	0	0	0	0	0	0	0	3
Innovations towards achieving environmentally sustainable operating theatres: A systematic review	Perry, H.; Reeves, N.; Ansell, J.; Cornish, J.; Torkington, J.; Morris, D. S.; Brennan, F.; Horwood, J.	1-6-2023	3	1	3	2	0	0	0	1	0	2	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0	0	0
Healing Patient, Harming Planet? Review of Waste Production and Recyclability of Surgical Instrument Packaging	Lee, Y. K.; Hariri, A.; Ghedia, R.; Tikka, T.; Kim, D.	1-1-2023	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Methods and evaluation metrics for reducing material waste in the operating room: a scoping review	Balch, J. A.; Krebs, J. R.; Filiberto, A. C.; Montgomery, W. G.; Berkow, L. C.; Upchurch, G. R.; Loftus, T. J.	1-1-2023	0	1	3	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Environmental impact of cardiovascular healthcare	Barratt, A. L.; Li, Y.; Gooroovadoo, I.; Todd, A.; Dou, Y.; McAlister, S.; Semsarian, C.	1-1-2023	0	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Sustainability across the Medical Device Lifecycle: A Scoping Review	Montesinos, L.; Rifa, P. C.; Fabregat, M. R.; Maldonado-Romo, J.; Capacci, S.; Maccaro, A.; Piaggio, D.	1-2-2024	3	1	3	3	3	2	0	3	3	2	0	0	1	0	0	3	1	1	0	1	1	1	0	0	0	0	0
Exploring Circular Economy Practices in the Healthcare Sector: A Systematic Review and Bibliometric Analysis	D'Alessandro, C.; Szopik-Depczynska, K.; Tarczynska-Luniewska, M.; Silvestri, C.; Ioppolo, G.	1-1-2024	0	1	3	3	0	1	3	1	0	3	1	0	3	0	0	2	1	3	0	0	0	0	0	0	0	0	1
The extent to which circular economy principles have been applied in the design of medical devices for low-resource settings in Sub-Saharan Africa. A systematic review	Samenjo, K. T.; Oosting, R. M.; Bakker, C.; Diehl, J. C.	1-4-2023	3	3	3	1	2	3	2	3	3	3	0	2	3	0	0	2	3	2	0	2	0	0	0	0	0	0	2
Circular economy for medical devices: Barriers, opportunities and best practices from a design perspective	Hoveling, T.; Nijdam, A. S.; Monincx, M.; Faludi, J.; Bakker, C.	1-9-2024	3	3	3	3	1	1	1	3	3	1	3	0	1	0	0	3	3	3	0	0	2	3	2	2	0	0	2
Healthcare waste in Bangladesh: Current status, the impact of Covid-19 and sustainable management with life cycle and circular economy framework	Dihan, M. R.; Abu Nayeem, S. M.; Roy, H.; Islam, M. S.; Islam, A.; Alsukaibi, A. K. D.; Awual, M. R.	1-5-2023	0	3	3	3	2	1	1	1	3	0	3	0	1	0	0	3	1	2	0	1	3	0	0	1	0	0	3
Current evidence on intermittent catheterization: sterile single-use catheters or clean reused catheters and the incidence of UTI	Getliffe, K.; Fader, M.; Allen, C.; Pinar, K.; Moore, K. N.	1-5-2007	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Environmental sustainability in healthcare: Time to make outpatient care in orthopaedics and rheumatology greener	Tsagkaris, C.; Nikolakea, M.; Laskaratou, E. D.; Samaras, C.; Huang, H.; Laubscher, L.; Bobirca, A.	1-5-2023	2	1	3	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
A review of Spaulding's classification system for effective cleaning, disinfection and sterilization of reusable medical devices: Viewed through a modern-day lens that will inform and enable future sustainability	Rowan, N. J.; Kremer, T.; McDonnell, G.	20-6-2023	0	2	3	2	1	1	0	1	1	2	1	0	1	0	1	1	1	3	0	0	2	2	0	0	0	0	3
Management of COVID-19 healthcare waste based on the circular economy hierarchy: A critical review	Voudrias, E. A.	27-9-2023	3	3	3	3	2	3	2	3	0	3	3	0	3	0	0	3	3	2	0	1	0	0	0	0	0	0	3
Barriers and enablers to implementing environmentally sustainable practices in healthcare: A scoping review and proposed roadmap	Aboueid, S.; Beyene, M.; Nur, T.	1-11-2023	0	1	1	3	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Waste management in the operating theatre	Talbot, S.; Moore, D.	1-1-2024	0	3	2	3	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
Making minimally invasive procedures more sustainable: A systematic review comparing the environmental footprint of single-use versus multi-use instruments	Martins, R. S.; Salar, H.; Salar, M.; Luo, J.; Poulikidis, K.; Razi, S. S.; Latif, M. J.; Tafuri, K.; Bhora, F. Y.	1-1-2024	0	0	2	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Environmental sustainability in obstetrics and gynaecology: A systematic review	Cohen, E. S.; Kouwenberg, L. H. J. A.; Moody, K. S.; Sperna Weiland, N. H.; Kringos, D. S.; Timmermans, A.; Hehenkamp, W. J. K.	1-1-2024	3	2	3	2	0	1	0	1	2	3	3	0	0	0	0	2	1	0	0	0	2	2	0	0	0	0	2
Barriers and facilitators to recycling waste in hospitals: A mixed methods systematic review	Jungbluth, L.; Goodwin, D.; Tull, F.; Bragge, P.	1-1-2024	0	1	2	1	0	0	0	0	0	0	1	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1
Environmental Impact of Flexible Cystoscopy: A Comparative Analysis Between Carbon Footprint of Isiris R Single-Use Cystoscope and Reusable Flexible Cystoscope and a Systematic Review of Literature	Jahrreiss, V.; Sarrot, P.; Davis, N. F.; Somani, B.	1-4-2024	0	0	3	2	0	1	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2

Digital technologies to unlock safe and sustainable opportunities for medical device and healthcare sectors with a focus on the combined use of digital twin and extended reality applications: A review	Rowan, N. J.	20-5-2024	0	1	3	2	2	2	0	0	0	1	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	2
Interventions to achieve environmentally sustainable operating theatres: an umbrella systematic review using the behaviour change wheel	Almukhtar, A.; Batcup, C.; Bowman, M.; Winter Beatty, J.; Leff, D.; Demirel, P.; Judah, G.; Porat, T.	2-8-2024	3	2	3	2	0	2	0	2	3	2	3	0	0	0	0	1	1	3	0	2	0	3	0	0	0	0	3
Improving Environmental Sustainability of Operating Theatres: A Systematic Review of Staff Attitudes, Barriers, and Enablers	Lodhia, S., Pegna, V., Abrams, R., Jackson, D., Rockall, T. A., Rizan, C.	10-5-2024	0	1	2	2	0	0	0	0	2	1	0	0	0	2	0	3	0	2	0	0	0	0	0	0	0	0	0
Circular business models in the medical device industry: paths towards sustainable healthcare	Guzzo, D.; Carvalho, M. M.; Balkenende, R.; Mascarenhas, J.	1-1-2020	0	1	2	1	2	2	0	0	0	2	0	3	3	0	2	3	2	2	0	0	2	0	0	0	0	0	0
Towards design strategies for circular medical products	Kane, G. M.; Bakker, C. A.; Balkenende, A. R.	1-9-2017	1	3	0	1	3	3	1	0	0	3	0	1	3	0	0	3	3	3	0	0	0	0	2	0	0	0	1
Big Data-Enabled Solutions Framework to Overcoming the Barriers to Circular Economy Initiatives in Healthcare Sector	Kazancoglu, Y.; Sagnak, M.; Lafci, C.; Luthra, S.; Kumar, A.; Tacoglu, C.	7-2-2021	2	2	2	2	1	0	2	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	0	0	0	0
Medical instrument reprocessing: current issues with cleaning and cleaning monitoring	Alfa, M. J.	6-2-2019	1	0	0	3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Surgical Instrument Reprocessing in Resource-Constrained Countries: A Scoping Review of Existing Methods, Policies, and Barriers	Forrester, J. A.; Powell, B. L.; Forrester, J. D.; Fast, C.; Weiser, T. G.	1-8-2018	0	0	0	0	2	2	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Effectiveness of autoclaving in sterilizing reusable medical devices in healthcare facilities	Panta, G.; Richardson, A. K.; Shaw, I. C.	10-2-2019	0	0	0	2	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Advances in Endoscope Reprocessing Technology and Its Impact on Pathogen Transmission	Shellnutt, C.	6-11-2016	1	0	0	2	0	2	0	0	0	3	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0
Environmental sustainability in robotic and laparoscopic surgery: systematic review	Papadopoulou, A.; Kumar, N. S.; Vanhoestenberghe, A.; Francis, N. K.	9-2-2022	2	2	3	2	0	0	0	0	0	1	0	0	0	0	3	0	3	2	0	0	0	3	0	0	0	0	0
Decontamination interventions for the reuse of surgical mask personal protective equipment: a systematic review	Zorko, D. J.; Gertsman, S.; O'Hearn, K.; Timmerman, N.; Ambu-Ali, N.; Dinh, T.; Sampson, M.; Sikora, L.; McNally, J. D.; Choong, K.	1-10-2020	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Revisiting the Evidence for the Reuse of Enteral Feeding Equipment in Ambulatory Patients: A Systematic Review	Osland, E. J.; Andersen, S.; Coleman, E.; Marshall, B.	1-1-2021	0	1	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Decontamination and reuse of surgical masks and N95 filteringfacepiece respirators during the COVID-19 pandemic: A systematic review	Seresirikachorn, K.; Phoophiboon, V.; Chobarporn, T.; Tiankanon, K.; Aeumjaturapat, S.; Chusakul, S.; Snidvongs, K.	1-1-2022	0	1	0	2	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
A framework for assessing the circularity and technological maturity of plastic waste management strategies in hospitals	Fletcher, C. A.; St Clair, R.; Sharmina, M.	1-7-2021	1	3	2	1	0	1	0	2	2	2	0	2	2	0	0	0	0	0	0	1	0	0	0	0	0	2	2
Circular economy adoption challenges in medical waste management for sustainable development: An empirical study	Kandasamy, J.; Kinare, Y. P.; Pawar, M. T.; Majumdar, A.; Vimal, K. E. K.; Agrawal, R.	1-10-2022	0	2	0	1	0	2	0	0	0	3	0	0	3	0	0	3	1	3	3	3	0	0	0	0	0	0	0
Possible involvement of reusable towels in the high rate of Bacillus species-positive blood cultures in Japanese hospitals	Saito, N.; Kondo, J.; Haruki, S.; Itoga, M.; Yamamoto, A.; Kimura, M.; Inoue, F.; Kobayashi, M.; Tsutaya, S.; Kojima, K.; Ueki, S.; Hirokawa, M.; Kayaba, H	1-1-2016	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Preventing infection from reusable medical equipment: a systematic review	Sopwith, W.; Hart, T.; Garner, P.	27-3-2001	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Infections and exposures: reported incidents associated with unsuccessful decontamination of reusable surgical instruments	Southworth, P. M.	1-11-2014	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Linking Environmental Sustainability, Health, and Safety Data in Health Care: A Research Roadmap	Kaplan, S. B.; Forst, L.	1-8-2017	2	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Environmental sustainability in hospitals – a systematic review and research agenda	McGain, F.; Naylor, C.	1-10-2014	2	2	2	2	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2
The Green Print: Advancement of Environmental Sustainability in Healthcare	Sherman, J. D.; Thiel, C.; MacNeill, A.; Eckelman, M. J.; Dubrow, R.; Hopf, H.; Lagasse, R.; Bialowitz, J.; Costello, A.; Forbes, M.; Stancliffe, R.; Anastas, P.; Anderko, L.; Baratz, M.; Barna, S.; Bhatnagar, U.; Burnham, J.; Cai, Y.; Cassels-Brown, A.; Cimprich, A. F. P.; Cole, H.; Coronado-Garcia, L.; Duane, B.; Grisotti, G.; Hartwell, A.; Kumar, V.; Kurth, A.; Leapman, M.; Morris, D. S.; Overcash, M.; Parvatker, A. G.; Pencheon, D.; Pollard, A.; Robaire, B.; Rockne, K.; Sadler, B. L.; Schenk, B.; Sethi, T.; Sussman, L. S.; Thompson, J.; Twomey, J. M.; Vermund, S. H.; Vukelich, D.; Wasim, N.; Wilson, D.; Young, S. B.; Zimmerman, J.; Bilec, M. M.	1-1-2020	0	1	3	3	0	0	0	0	3	3	0	0	0	0	0	0	3	2	0	0	0	2	0	2	0	0	3
A Roadmap for Environmental Sustainability of Plastic Use in Anesthesia and the Perioperative Arena	Xiao, M. Z. X.; Abbass, S. A. A.; Bahrey, L.; Rubinstein, E.; Chan, V. W. S.	10-2-2021	0	1	3	1	0	0	0	1	2	3	0	0	0	2	0	1	1	1	0	3	0	3	0	0	0	0	1
Extended use or reuse of single-use surgical masks and filtering face-piece respirators during the coronavirus disease 2019 (COVID-19) pandemic: A rapid systematic review	Toomey, E. C.; Conway, Y.; Burton, C.; Smith, S.; Smalle, M.; Chan, X. S.; Adisesh, A.; Tanveer, S.; Ross, L.; Thomson, I.; Devane, D.; Greenhalgh, T.	1-2-2021	0	0	0	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Performance and impact of disposable and reusable respirators for healthcare workers during pandemic respiratory disease: a rapid evidence review	Burton, C.; Coles, B.; Adisesh, A.; Smith, S.; Toomey, E.; Chan, X. H. S.; Ross, L.; Greenhalgh, T.	9-2-2021	0	0	0	3	0	0	0	3	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Reuse of single use medical devices in Canada: Clinical and economic outcomes, legal and ethical issues, and current hospital practice	Hailey, D.; Jacobs, P. D.; Ries, N. M.; Polisena, J.	1-9-2008	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reusable and disposable insulin pens for the treatment of diabetes: understanding the global differences in user preference and an evaluation of inpatient insulin pen use	Perfetti, R.	1-6-2010	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Disposable face masks and reusable face coverings as non-pharmaceutical interventions (NPIs) to prevent transmission of SARS-CoV-2 variants that cause coronavirus disease (COVID-19): Role of new sustainable NPI design innovations and predictive mathematical modelling	Rowan, N. J.; Moral, R. A.	10-6-2021	3	3	0	3	0	0	0	0	0	1	0	3	0	0	0	0	0	2	0	0	2	2	0	0	0	0	0
Addressing the environmental sustainability of eye health-care delivery: a scoping review	Buchan, J. C.; Thiel, C. L.; Steyn, A.; Somner, J.; Venkatesh, R.; Burton, M. J.; Ramke, J.	6-2-2022	0	1	2	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2
Environmental sustainability in anaesthesia and critical care	McGain, F.; Muret, J.; Lawson, C.; Sherman, J. D.	12-8-2020	0	2	1	1	0	0	0	0	0	3	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0	2
Environmentally sustainable dermatology	Allwright, E.; Abbott, R. A.	23-2-2023	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2
Considerations for environmentally sustainable head and neck surgical oncology practice	Sanabria, A.; Kowalski, L. P.; Nixon, I. J.; Shaha, A.; De Bree, R.; Makitie, A. A.; Rinaldo, A.; Ferlito, A.	1-11-2020	3	2	3	3	0	0	0	0	3	3	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0
Barriers to environmentally sustainable initiatives in oral health care clinical settings	de Leon, M. L.	10-2-2020	0	1	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
Environmental sustainability in healthcare: Time to make outpatient care in orthopaedics and rheumatology greener	Tsagkaris, C.; Nikolakea, M.; Laskaratou, E. D.; Samaras, C.; Huang, H.; Laubscher, L.; Bobirca, A.	14-2-2023	2	2	2	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0
Biopolymer: A Sustainable Material for Food and Medical Applications	Baranwal, J.; Barse, B.; Fais, A.; Delogu, G. L.; Kumar, A.	28-2-2022	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	3	0	0	0
Greener Operations: a James Lind Alliance Priority Setting Partnership on environmentally sustainable peri-operative practice	Clayton-Smith, M.; Narayanan, H.; Shelton, C.; Bates, L.; Brennan, F.; Deido, B.; Donnellon, M.; Dorey, J.; Evans, B.; Gower, J.; Hamdaoui, Y.; Hitchman, J.; Kinsella, S. M.; Knagg, R.; Lawson, C.; Morris, D.; Pegna, V.; Radcliffe, T.; Schaff, O.; Sheppard, T.; Strong, J.; Jones, D.	1-1-2016	2	2	2	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
Environmental Sustainability in Orthopaedic Surgery	Engler, I. D.; Curley, A. J.; Fu, F. H.; Bilec, M. M.	1-6-2022	0	2	3	2	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Greening the operating room	Guetter, C. R.; Williams, B. J.; Slama, E.; Arrington, A.; Henry, M. C.; Moller, M. G.; Tuttle-Newhall, J. E.; Stein, S.; Crandall, M.	10-2-2018	0	3	3	3	1	0	0	1	2	1	0	0	0	2	0	0	0	0	0	0	0	3	0	0	0	0	0
Greening the operating room	Papadopoulou, A.; Kumar, N. S.; Vanhoestenberghe, A.; Francis, N. K.	9-2-2022	2	2	3	2	0	0	0	0	0	1	0	0	0	0	3	0	3	2	0	0	0	3	0	0	0	0	0
Innovations towards achieving environmentally sustainable operating theatres: A systematic review	Perry, H.; Reeves, N.; Brennan, F.; Morris, D.; Torkington, J.; Horwood, J.	28-4-2022	2	2	3	3	0	0	0	1	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Environmental Sustainability in the Orthopaedic Operating Room	Smith, J. T.; Boakye, L. A. T.; Ferrone, M. L.; Furie, G. L.	11-2-2022	0	2	3	2	3	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Initiatives to broaden safety concerns in anaesthetic practice: The green operating room	Beloeil, H.; Albaladejo, P.	1-5-2021	0	2	1	3	0	0	0	0	3	3	3	0	0	3	0	0	0		0	0	0	0	0	0	0	0	0
Empowering Surgeons, Anesthesiologists, and Obstetricians to Incorporate Environmental Sustainability in the Operating Room	Yates, E. F.; Bowder, A. N.; Roa, L.; Velin, L.; Goodman, A. S.; Nguyen, L. L.; McClain, C. D.; Meara, J. G.; Cooper, Z.	6-2-2021	3	1	3	3	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3
Environmental sustainability in orthopaedic surgery : a scoping review	Phoon, K. M.; Afzal, I.; Sochart, D. H.; Asopa, V.; Gikas, P.; Kader, D.	1-8-2022	1	2	3	3	0	0	0	0	2	3	0	0	0	3	0	0	0	0	0	0	1	0	0	0	0	0	0

APPENDIX G. Full table of terms and definitions

Table 11
Analysis of terms and definitions from full-text analysis (n = 68 total reviewed)

Term used for CE strategy (mentioned by # of reviewed articles; n = 68)	Healthcare literature (from review)	Healthcare bodies	Non-healthcare bodies	Circular economy frameworks	Manner of integrating into visual taxonomy
	Meaning of term use in review articles	Definitions from MDR-EU 2017/745 (MDR) and FDA medical device regulation (FDA)	Definitions from Waste Framework Directive (WFD) ISO 59004:2024 (ISO), and Re-defining Value report (UNEP)	Definitions from EMF Butterfly Diagram (EMF), PBL 10R framework (PBL), and Value Hill (VH)	
Reuse (62)	• Reusing is the opposite of a disposable/single use **(18x)** • Using devices again after decontamination **(17x)** • Using the same device on multiple patients **(7x)** • Reusing single-use or disposable devices **(5x)** • Using materials again **(1x)** • Using devices again on the same patient (single-patient reuse) **(1x)**	• "Reusable medical devices are devices that health care providers can reprocess and reuse on multiple patients." (FDA (Center for Devices and Radiological Health, 2018))	• "Operation by which products or components that are not waste are used again for the same purpose for which they were conceived." (WFD (Directive, 2008, 2018)) • "Use a product or its component parts after their initial use, for the same purpose for which they were originally designed." (ISO ()) • "Using again of a product, object or substance that is not waste, for the same purpose for which it was conceived, without the necessity of repair or refurbishment." (UNEP [10])	• "The repeated use of a product or component for its intended purpose without significant modification." (EMF (EllenMacArthur Foundationa)) • "Re-use by another consumer of discarded product which is still in good condition and fulfils its original function." (PBL (Potting et al., 2017))	Included as the fifth circularity strategy.
Reduce (54)	• Reducing waste **(29x)** • Reducing resources (including materials, energy use, and water use in production and use) **(29x)** • Reduce environmental impact **(19x)** • Reduce healthcare care need (e.g. reducing sterilization risks)/ unnecessary care **(13x)** • Reducing use of unsustainable devices (e.g. disposable, non-recyclable, unnecessary packaging) **(4x)** • Reducing use of chemicals/toxins **(3x)** • Reducing need for novel products and equipment **(2x)**	No definition available	No definition available	• "Increase efficiency in product manufacture or use by consuming fewer natural resources and materials." (PBL (Potting et al., 2017))	Included as the fourth circularity strategy.
Recycle (53)	• Reusing raw material after processing (decontaminate, shred, melt and remould) **(10x)** • Sterilize and reuse device/ component/material **(2x)** • Chemical recycling **(1x)**	• "The processing of waste to make new articles." (FDA (Center for Food Safety and Applied Nutrition, 2024))	• "Any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes." (WFD (Directive, 2008, 2018)) • "Activities to obtain recovered resources for use in a process or a product, excluding energy recovery." (ISO ()) • "Operations usually involve the reprocessing of waste into products, materials, or substances, though not necessarily for the original purpose, and does not cover operations that recover energy from waste." (UNEP [10])	• "Transform a product or component into its basic materials or substances and reprocessing them into new materials." (EMF (EllenMacArthur Foundationa)) • "Process materials to obtain the same (high grade) or lower (low grade) quality." (PBL (Potting et al., 2017)) • "Recycling facility transforms waste into raw materials." (VH (Achterberg et al., 2016))	Included as the eleventh circularity strategy.

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Table 11 (*continued*)

Term used for CE strategy (mentioned by # of reviewed articles; n = 68)	Healthcare literature (from review) Meaning of term use in review articles	Healthcare bodies Definitions from MDR-EU 2017/745 (MDR) and FDA medical device regulation (FDA)	Non-healthcare bodies Definitions from Waste Framework Directive (WFD) ISO 59004:2024 (ISO), and Re-defining Value report (UNEP)	Circular economy frameworks Definitions from EMF Butterfly Diagram (EMF), PBL 10R framework (PBL), and Value Hill (VH)	Manner of integrating into visual taxonomy
Reprocess (48)	• Decontaminate (+package) single-use devices for reuse **(17x)** • Decontamination or reusables **(13x)** • Decontamination process + reuse process **(1x)** • Overarching term for all R-strategies **(1x)** • Product recovery after repair, cleaning, sterilization and repackaging **(1x)**	• "A process carried out on a used device in order to allow its safe reuse including cleaning, disinfection, sterilization and related procedures, as well as testing and restoring the technical and functional safety of the used device." (MDR (MDR-EU, 2017, 2017)) • "A process carried out on a used device in order to allow its safe reuse. It includes its cleaning, disinfection, sterilization and related procedures, as well as testing and restoring the technical and functional safety of the used device." (FDA (Center for Devices and Radiological Health, 2020))	No definition available	No definition available	Overarching term to describe end of use strategies that maintain product integrity (*reuse*, *maintain*, *repair*, *refurbish*, and *remanufacture*).
Prevent (32)	Prevent … • Decontaminate (+package) single-use devices for reuse **(17x)** • … (unnecessary) care and device consumption (including e.g. preventive care and infection prevention) **(19x)** • … climate change/ pollution **(9x)** • … waste (including e.g. use of disposables and disposal of unused but opened instruments) **(7x)** • … product obsolescence (including preventive maintenance) **(6x)** • … material scarcity **(1x)** • … mixed waste streams **(1x)**	No definition available	• "Measures taken before a substance, material or product has become waste, that reduce: (a) the quantity of waste, including through the re-use of products or the extension of the life span of products; (b) the adverse impacts of the generated waste on the environment and human health; or (c) the content of hazardous substances in materials and products." (WFD (Directive, 2008, 2018))	No definition available	Partially disregarded due to too broad definition scope (e.g., preventing climate change), and partially scaled under *refuse* (completely refusing device use or unnecessary procedures), *replace* (substituting devices or procedures by more sustainable alternatives), and *reduce* (minimizing unnecessary device use and procedures).
(Re)design (32)	• Design for sustainability/ circularity (enabling R-strategies) **(41x)** *including design for …* o … sterilization **(6x)** o … waste management **(3x)** o … waste reduction **(3x)** o … recyclability **(3x)** o … behavioural change **(2x)** o … durability **(2x)** o … eco-design **(1x)** o … maintenance **(1x)** o … modularity **(1x)** o … refurbishment **(1x)** o … end-of-life **(1x)** o … disassembly **(1x)**	No definition available	• Eco-design is "design and development based on a life cycle perspective aimed at supporting sustainable development." (ISO ()) • Design for circularity is "design and development based on the circular economy principles." (ISO ())	• "Designing products with their end-of-life in mind by making them easy to maintain, repair, upgrade, refurbish or remanufacture." (VH (Achterberg et al., 2016))	Partially disregarded and partially scaled under other strategies, as this could refer to the *(re)design* of a product or procedure to enable any of the other strategies (e.g. to *rethink* the system, to *replace* the product or even to *reduce* energy consumption), making the term in itself too broad to include separately.
Replace (31)	• Replace with more sustainable alternative (e.g. reusable or recyclable	No definition available	No definition available	No definition available	Included as the second circularity strategy.

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Table 11 (*continued*)

Term used for CE strategy (mentioned by # of reviewed articles; n = 68)	Healthcare literature (from review) Meaning of term use in review articles	Healthcare bodies Definitions from MDR-EU 2017/745 (MDR) and FDA medical device regulation (FDA)	Non-healthcare bodies Definitions from Waste Framework Directive (WFD) ISO 59004:2024 (ISO), and Re-defining Value report (UNEP)	Circular economy frameworks Definitions from EMF Butterfly Diagram (EMF), PBL 10R framework (PBL), and Value Hill (VH)	Manner of integrating into visual taxonomy
	vs. disposable alternative) **(23x)** *including* … o … Replacing materials **(11x)** o … Replacing equipment **(12x)** o … Replacing procedures **(5x)** • Digitization **(5x)** • Replacing parts or components in repair or remanufacturing **(4x)**				
Maintain (23)	• Preventive maintenance **(8x)** • Maintain clinical environment quality and safety (including preventive maintenance) **(7x)** • Lifetime extension **(2x)** • Maintaining value **(2x)** • Maintaining availability **(1x)** • Corrective maintenance **(1x)**	• "Servicing is the repair and/or preventive or routine maintenance of one or more parts in a finished device, after distribution, for purposes of returning it to the safety and performance specifications established by the original equipment manufacturer (OEM) and to meet its original intended use." (FDA (FDA, 2024))	No definition available	• "Keep a product in its existing state of quality, functionally and/or cosmetically, to guard against failure or decline. It is a practice that retains the highest value of a product by extending its use period." (EMF (EllenMacArthur Foundationa)) • "Repair and maintenance of defective product so it can be used with its original function." (PBL (Potting et al., 2017)) • "Repair & Maintenance Service repairs, maintains, and possibly upgrades products that are still in use." (VH (Achterberg et al., 2016))	Included as the sixth circularity strategy.
Repair (22)	• Recover functional obsolescence (corrective maintenance) **(6x)** • Lifetime extension **(5x)**	• "Servicing is the repair and/or preventive or routine maintenance of one or more parts in a finished device, after distribution, for purposes of returning it to the safety and performance specifications established by the original equipment manufacturer (OEM) and to meet its original intended use." (FDA, (FDA, 2024))	• "Restore a product to a condition needed for the product to function according to its intended purpose." (ISO ()) • "Fixing of a specified fault in an object that is a waste or a product and/or replacing defective components, in order to make the waste or product a fully functional product to be used for its originally intended purpose." (UNEP [10])	• "Operation by which a faulty or broken product or component is returned back to a useable state to fulfil its intended use." (EMF (EllenMacArthur Foundationa)) • "Repair and maintenance of defective product so it can be used with its original function." (PBL (Potting et al., 2017)) • "Repair & Maintenance Service repairs, maintains, and possibly upgrades products that are still in use." (VH (Achterberg et al., 2016))	Included as the seventh circularity strategy.
Recover (21)	• Recover/retain material/ waste **(15x)** *Including* … o … through recycling **(2x)** o … for recycling **(1x)** • Energy recovery (incineration) **(5x)** • Recover product/material value **(3x)** • Overarching term for all R-strategies **(1x)**	No definition available	• "Any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Annex II sets out a non-exhaustive list of recovery operations." (WFD (Directive, 2008, 2018)) • Energy recovery is the "generation of useful	• "Incineration of materials with energy recovery." (PBL (Potting et al., 2017)) • "Recovery provider provides take back systems and collection services to recover useful resources out of disposed products or by-products." (VH (Achterberg et al., 2016))	Part of the definitions were disregarded as being too broad. However, *recover energy* (through incineration) was included as the thirteenth (last) circularity strategy.

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Table 11 (*continued*)

Term used for CE strategy (mentioned by # of reviewed articles; n = 68)	Healthcare literature (from review) Meaning of term use in review articles	Healthcare bodies Definitions from MDR-EU 2017/745 (MDR) and FDA medical device regulation (FDA)	Non-healthcare bodies Definitions from Waste Framework Directive (WFD) ISO 59004:2024 (ISO), and Re-defining Value report (UNEP)	Circular economy frameworks Definitions from EMF Butterfly Diagram (EMF), PBL 10R framework (PBL), and Value Hill (VH)	Manner of integrating into visual taxonomy
			energy through direct and controlled transformation of recovered resources." (ISO ()) • Recoverable resource is a "resource that can be recovered and used again after it has already been processed or used." (ISO ()) • Recover value is the "process to recuperate the value of the object of consideration." (ISO ())		
Remanufacture (19)	• Provide used equipment in as new or better than new condition through cleaning, significant renovation, quality control, and repackaging **(5x)** • Products back into service after parts replacement **2x)** • Clean & pack SUDs for reuse **(1x)** • Clean, quality control, certification, repack, redistribute SUDs **(1x)**	• "The processing, conditioning, renovating, repackaging, restoring, or any other act done to a finished device that significantly changes the finished device's performance or safety specifications, or intended use." (FDA (FDA, 2024))	• "Return an item to a like-new condition from both a quality and performance perspective using an industrial process." (ISO ()) • **"**A standardized industrial process that takes place within industrial or factory settings, in which cores are restored to original as-new condition and performance, or better. The remanufacturing process is in line with specific technical specifications, including engineering, quality, and testing standards, and typically yields fully warranted products." (UNEP [10]**)** • "Re-engineer products and components to as-new condition with the same, or improved, level of performance as a newly manufactured one." (EMF (EllenMacArthur Foundationa))	• "Use parts of discarded product in a new product with the same function." (PBL (Potting et al., 2017)) • "Remanufacturer provides products from recaptured materials and components." (VH (Achterberg et al., 2016))	Included as the ninth circularity strategy.
Rethink (18)	• Making systems/processes more environmentally sustainable **(9x)** *including* … o … patient transport **(2x)** o … purchasing **(2x)** o … telemedicine **(2x)** o … packaging strategy **(1x)** o … production **(1x)** o … delivery **(1x)** • Sustainable redesign of product and procedures **(3x)** • Avoid unnecessity treatment/resources **(3x)** • Changing beliefs and practices **(2x)** • Choose sustainable alternative **(1x)** • Reduce length of hospital stay **(1x)** • Intensify product utilization **(1x)**	No definition available	No definition available	• "Make product use more intensive (e.g. through sharing products, or by putting multi-functional products on the market)" (PBL (Potting et al., 2017))	Included as the third circularity strategy, merging the healthcare definitions (sustainability system adaptations) with the PBL definition.
Renew (17)	• Renewable energy **(8x)**	No definition available	• 1) Renewable energy: "energy from a renewable	• 1) Renewable materials: "materials that are	Included as the twelfth circularity strategy.

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Table 11 (*continued*)

Term used for CE strategy (mentioned by # of reviewed articles; n = 68)	Healthcare literature (from review)	Healthcare bodies	Non-healthcare bodies	Circular economy frameworks	Manner of integrating into visual taxonomy
	Meaning of term use in review articles	Definitions from MDR-EU 2017/745 (MDR) and FDA medical device regulation (FDA)	Definitions from Waste Framework Directive (WFD) ISO 59004:2024 (ISO), and Re-defining Value report (UNEP)	Definitions from EMF Butterfly Diagram (EMF), PBL 10R framework (PBL), and Value Hill (VH)	
	• Using biodegradable polymers **(4x)** • Repair or remanufacturing **(1x)**		resource.“, 2) Renewable resource: “resource that can be naturally or artificially grown or replenished within a foreseeable time frame by processes found in nature.” (ISO ())	continually replenished at a rate equal to or greater than the rate of depletion.“, 2) Renewable energy: “energy derived from resources that are not depleted on timescales relevant to the economy, i.e. not geological timescales.” (EMF (EllenMacArthur Foundationa))	
Repurpose (15)	• Use discarded product for different purpose or function **(3x)** • Use discarded product in a different context (including environmental restructuring) **(3x)** • Use discarded product/ part in new product (with a different function) **(3x)** • Use discarded product/ part in different location (e.g. developing countries) **(2x)** • Maximize product life cycle **(1x)**	No definition available	• “Adapt a product or its component parts for use in a different function than it was originally intended for, without making major modifications to its physical, chemical or mechanical structure.” (ISO ())	• “Use discarded product or its parts in a new product with a different function.” (PBL (Potting et al., 2017))	Included as the tenth circularity strategy.
Refurbish (13)	• Transform obsolete products to contemporary standards (e.g. performance, safety) while remaining intended use **(3x)** • Like remanufacturing, bring device into conformity with regulation **(3x)** • Put back into service after parts replacement (resulting is lower quality) **(2x)** • Repair, upgrades, cosmetic changes, performance check, reinstallation, warranty **(2x)**	• “The complete rebuilding of a device already placed on the market or put into service, or the making of a new device from used devices, to bring it into conformity with this Regulation, combined with the assignment of a new lifetime to the refurbished device.” (MDR (MDR-EU, 2017, 2017))	• “Restore an item, during its expected service life, to a useful condition for the same purpose with at least similar quality and performance.” (ISO ()) • “Modification of an object that is a waste or a product that takes place within maintenance or intermediate maintenance operations to increase or restore performance and/ or functionality or to meet applicable technical standards or regulatory requirements, with the result of making a fully functional product to be used for a purpose that is at least the one that was originally intended. The restoration of functionality, but not value, enables a partial new service life for the product.“(UNEP [10])	• “Restore an old product and bring it up to date.” (PBL (Potting et al., 2017)) • “Return a product to good working order. This can include repairing or replacing components, updating specifications, and improving cosmetic appearance.” (EMF (EllenMacArthur Foundationa)) • “Refurbisher refurbishes used products if necessary and re-sells them.” (VH (Achterberg et al., 2016))	Included as the eighth circularity strategy.
Biodegrade (11)	• Using biodegradable polymers (intended for composting) **(6x)** • Using biodegradable medications **(2x)** • Using biodegradable coating **(1x)** • Energy recovery **(1x)**	No definition available	No definition available	• “Able to be broken down into carbon dioxide, water, and biomass by the natural action of microorganisms over an unspecified length of time and in undefined conditions.” (EMF (EllenMacArthur Foundationb))	Scaled under the definition of *renew*.
Refuse (10)	• Refuse disposal/prevent waste **(2x)** • Refuse (new) devices **(2x)** • Refuse harmful substances **(1x)** • Refuse consumption **(1x)**	No definition available	No definition available	• “Make product redundant by abandoning its function or by offering the same function with a radically different product.” (PBL (Potting et al., 2017))	Included as the first circularity strategy.

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Table 11 (*continued*)

Term used for CE strategy (mentioned by # of reviewed articles; n = 68)	Healthcare literature (from review) Meaning of term use in review articles	Healthcare bodies Definitions from MDR-EU 2017/745 (MDR) and FDA medical device regulation (FDA)	Non-healthcare bodies Definitions from Waste Framework Directive (WFD) ISO 59004:2024 (ISO), and Re-defining Value report (UNEP)	Circular economy frameworks Definitions from EMF Butterfly Diagram (EMF), PBL 10R framework (PBL), and Value Hill (VH)	Manner of integrating into visual taxonomy
	• Refuse purchase **(1x)** • Refuse redundant products, procedures and services **(1x)** • Refuse non-circular practices **(1x)**				
Restore (9)	• Restore value **(2x)** • "Repair" product/material **(3x)** • Restore trust in circular device **(1x)**	No definition available	No definition available	No definition available	Scaled under the definition of *repair*.
Closing loops (9)	• Developing value from waste **(2x)** • Minimizing waste **(1x)** • Analogy for "circular economy": resources that have entered this loop remain accounted for **(1x)**	No definition available	• Closed loop system is a "system by which products or resources are used and then recovered and turned into new products or recovered resources, without losing their inherent properties." (ISO ())	No definition available	Excluded due to limited clarity in definitions while also encompassing multiple other strategies.
Research (8)	• Life cycle analyses **(4x)** • "Green" device development **(3x)** • Cost comparisons **(1x)** • Renewable energy source **(1x)** • Lean & 6-sigma methods **(1x)**	No definition available	No definition available	No definition available	Disregarded due to it having a too broad definition and not describing one circularity strategy on its own.
Retain (5)	• Retaining value in circularity **(4x)** • Retaining value by recycling **(2x)** • Retain product use over time **(1x)** • Retain functionality in CE **(1x)**	No definition available	No definition available	No definition available	Partially scaled under maintain, partially disregarded due to vague definitions in literature.
Regenerate (4)	• Regenerative medicine **(1x)** • Regenerating natural systems (e.g. composting or anaerobic digestion) **(2x)**	No definition available	• "Improve or restore a degraded ecosystem." (ISO ())	• "*Regenerative production* provides food and materials in ways that support positive outcomes for nature, which include but are not limited to: healthy and stable soils, improved local biodiversity, improved air and water quality." (EMF (EllenMacArthur Foundationa))	Scaled under the definition of *renew*.
Redistribute (4)	• One of the technical circular cycles **(1x)**	No definition available	No definition available	• "Divert a product from its intended market to another customer so it is used at high value instead of becoming waste." (EMF (EllenMacArthur Foundationa)) • While not providing a direct definition, (Achterberg et al., 2016) seems to use *redistribute* as a term to indicate an essential part of *reuse*. (VH (Achterberg et al., 2016))	Integrated as a part of the strategies for which (re)distribution is needed in the processes performed after the use cycle.
Share (3)	• Sharing of products or equipment **(2x)**	No definition available	No definition available	• "The use of a product by multiple users. It is a practice that retains the highest value of a product by extending its use period." (EMF	Scaled under the definition of *rethink*, following the PBL definition.

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Table 11 (*continued*)

Term used for CE strategy (mentioned by # of reviewed articles; n = 68)	Healthcare literature (from review) Meaning of term use in review articles	Healthcare bodies Definitions from MDR-EU 2017/745 (MDR) and FDA medical device regulation (FDA)	Non-healthcare bodies Definitions from Waste Framework Directive (WFD) ISO 59004:2024 (ISO), and Re-defining Value report (UNEP)	Circular economy frameworks Definitions from EMF Butterfly Diagram (EMF), PBL 10R framework (PBL), and Value Hill (VH)	Manner of integrating into visual taxonomy
				(EllenMacArthur Foundationa)) • "Sharing Platforms enable an increased utilization rate of products by enabling or offering shared use/access or ownership through which, different users use the product sequentially."(VH (Achterberg et al., 2016))	
Resterilise (2)	• Sterilizing (again) for reuse **(1x)**	No definition available	No definition available	No definition available	Integrated as a part of the strategies for which sterilization is needed in the processes performed after the use cycle.
Slowing loops (1)	• Durable design **(1x)** • Enabled by reuse **(1x)** • Increasing product longevity **(1x)**	No definition available	No definition available	No definition available	Excluded due to limited clarity in definitions while also encompassing multiple other strategies.
(bio)remediate (1)	• "The use of a product by multiple users. It is a practice that retains the highest value of a product by extending its use period." (EMF (EllenMacArthur Foundationa)) • Chemical recycling by microbial action **(1x)**	No definition available	No definition available	No definition available	Scaled under the definition of *renew*.

APPENDIX H. PRACTICAL APPLICATION OF VISUAL TAXONOMY

This appendix illustrates the practical application of the proposed visual taxonomy through a concise case study focused on the lifecycle management of an endoscope. This example demonstrates how circular economy (CE) strategies can guide decision-making at various stages—from research and design through reuse, refurbishment, and end-of-life treatment. To ground the theoretical framework in a real-world healthcare context, Table 12 presents a detailed, chronological overview of key CE considerations, responsible actors, required information, expected conclusions, and recommended actions specific to the endoscope lifecycle.

The case centres on the intended circular design of an endoscope—a flexible medical device primarily used for internal diagnostic and therapeutic procedures in minimally invasive surgeries. Its main functions include visualizing internal organs, collecting biopsy samples, and enabling targeted interventions.

Following the *Circular Healthcare Flows visual*, the table walks through a step-by-step decision-making process across different CE strategies in chronological order. It is important to note that actions linked to different strategies may sometimes conflict. While prioritizing higher-level CE strategies in the hierarchy is generally advised, decisions must be context sensitive. For instance, if reuse requires design choices (e.g., screws for easy disassembly) that complicate recycling, a system-level sustainability assessment should inform the trade-off rather than opting blindly for one strategy.

The table's responsible actors reflect the specific endoscope context: since the device is used mainly within hospitals and rarely by patients themselves, patient responsibility in CE strategy application is minimal during active use.

Lastly, the visual taxonomy emphasizes potential transitions and failure modes between CE strategies. Though detailed scenarios of such transitions are beyond this example's scope, users are encouraged to consider contingencies—for example, if an endoscope fails to meet reuse quality standards after reprocessing, should it proceed to refurbishment, remanufacturing, or recycling?

Table 12
Endoscope example of CE strategy considerations

Visual Taxonomy Stage	CE Strategy Consideration	Main Responsible Actor(s)	Required Information for Endoscope Case	Expected Conclusion	Examples of Recommended Actions
Research, Design, and Development	**Refuse** — rejecting device use if function can be avoided	Manufacturer, Healthcare Facility	- Core device function - Added clinical value - Harm/risk from refusal	Endoscope essential for diagnosis and therapy; refusal compromises patient care	Refusal is not feasible in this case; proceed only when clinically necessary.

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Table 12 (*continued*)

Visual Taxonomy Stage	CE Strategy Consideration	Main Responsible Actor(s)	Required Information for Endoscope Case	Expected Conclusion	Examples of Recommended Actions
Research, Design, and Development	**Replace** — substitute device with lower-impact alternative	Manufacturer, Healthcare Facility	- Functional equivalence of alternatives - Environmental impact of alternatives	Alternatives (e.g., capsule endoscopy, imaging) lack full therapeutic capability; unclear environmental benefit	Replacement is not worthwhile for full function; continue with endoscope and explore other CE strategies.
Research, Design, and Development	**Rethink** — systemically enhance procedures for sustainability	Manufacturer, Healthcare Facility, Service Providers	- Potential for device sharing - Multifunctionality opportunities - Feasibility of use in other care settings	Endoscopes can support combined diagnostic-therapeutic use, shared across departments to reduce device numbers	Implement device-sharing programs, combine diagnostic-therapeutic sessions, and enable multifunctional use and shared clinician training.
Research, Design, and Development	**Reduce** — minimize resource use and unnecessary procedures	Manufacturer, Healthcare Facility, Patient	- Procedure frequency rationale - Consumables per procedure - Energy/water consumption	Reducing unnecessary procedures and consumables lowers environmental footprint	Perform only clinically necessary procedures, minimize disposable accessory use, and optimize sterilization processes.
Performance Sustainment	**Maintain** — preserve function to extend lifespan	Healthcare Facility, Service Providers, Manufacturer	- Maintenance schedules - Usage logs	Regular maintenance prevents premature replacement and ensures safety	Implement strict maintenance protocols, provide staff training, and track device usage for timely upkeep.
Performance Sustainment	**Repair** — restore faulty components	Manufacturer, Service Providers, Healthcare Facility	- Common failure modes - Repair feasibility-Safety standards	Typical failures (light cables, insertion tubes, lenses, controls) are repairable under safety standards	Prioritize durable design of critical parts and facilitate easy repair and replacement processes.
Reprocessing for Intended Use	**Reuse** — reuse components after decontamination	Healthcare Facility, Service Providers, Manufacturer	- Decontamination protocols - Component reusability limits - Traceability requirements	Reuse feasible with appropriate sterilization and traceability; extends device lifespan	Design for durability and easy disassembly; develop validated decontamination protocols and maintain traceability.
Reprocessing for Intended Use	**Refurbish** — restore devices to good condition	Manufacturer, Service Providers	- Device condition assessment - Repair/upgrade needs - Refurbish cycle limits - Traceability	Some components fail earlier; refurbishment restores function and safety	Enable easy dismantling and repair; set refurbishment limits per component; ensure traceability throughout.
Reprocessing for Intended Use	**Remanufacture** — restore devices to as-new condition	Manufacturer, Service Providers	- Device condition post-refurbishment - Component availability - Certification - Updateability	After multiple reuse/refurbish cycles, full remanufacturing required for safety and modernization	Recover reusable components to produce as-new devices, meeting certification and updating standards as needed.
End of Intended Use Transformations	**Repurpose** — use discarded parts for new purposes	Manufacturer, Service Providers	- Alternative safe applications - Regulatory considerations	Parts may be reused for training, veterinary use, or in resource-limited settings	Repurpose safe components for training, veterinary care, or low-resource settings following safety regulations.
End of Intended Use Transformations	**Recycle** — convert materials into raw materials	Recycler, Hazardous Waste Facility, Service Providers	- Material composition - Recycling feasibility and logistics	Metals and some plastics recyclable but challenging separation; many plastics non-recyclable	Design for minimal material variety and easy separation; establish take-back schemes to improve recycling rates.
End of Intended Use Transformations	**Renew** — convert materials via natural processes	Composting Plants, Healthcare Facility	- Biodegradability of components - Suitability for regenerative processes	Limited applicability; biodegradable components minimal, no implantable residues	Renew is not feasible; components at end-of-life should be recycled or incinerated.
Leakage	**Recover Energy** — incinerate waste for energy recovery	Waste Incineration Plant, Healthcare Facility	- Incineration requirements - Medical waste protocols - Energy recovery efficiency	Non-recyclable parts safely incinerated with energy recovery; medical incineration standards met	Incinerate non-recyclable components in compliant medical waste facilities to recover energy while ensuring safety.

Based on this exercise, the principal recommendations for the endoscope emphasize enabling sustainable clinical use without compromising patient care. Complete refusal or replacement with alternatives is generally not feasible given the device's indispensable diagnostic and therapeutic functions. Instead, efforts should prioritize rethinking clinical workflows to facilitate device sharing and multifunctionality, alongside reducing unnecessary procedures and consumable usage to lower resource consumption. Extending the device's functional lifespan through rigorous maintenance, repair, and validated reuse protocols is critical. Upon reaching component end-of-life, refurbishment and remanufacturing should be employed to restore safety and performance. At end-of-life, repurposing safe parts, enhancing recyclability through design for disassembly and material selection, and safe energy recovery via incineration constitute key strategies to minimize environmental impact. Collectively, these recommendations represent a coherent, context-sensitive circular approach tailored to the unique requirements of endoscope lifecycle management.

Data availability

No data was used for the research described in the article.

References

ISO 59004:2024(en). Circular economy — vocabulary, principles and guidance for implementation [Internet]. [cited 2024 Jul 4]. Available from: https://www.iso.org/obp/ui#iso:std:iso:59004:ed-1:v1:en.

Achterberg, E., Hinfelaar, J., Bocken, N., 2016. Master circular business models with the value hill [Internet]. https://circulareconomy.europa.eu/platform/en/knowledge/master-circular-business-value-hill. (Accessed 22 November 2022).

Bramer, W.M., 2018. Reference checking for systematic reviews using endnote. J Med Libr Assoc JMLA 106 (4), 542–546.

Bramer, W., Bain, P., 2017. Updating search strategies for systematic reviews using EndNote. J Med Libr Assoc JMLA 105 (3), 285–289.

Bresciani, S., 2019. Visual design thinking: a collaborative dimensions framework to profile visualisations. Des. Stud. 63, 92–124.

Center for Devices and Radiological Health, 2018. What are reusable medical devices? FDA [Internet]. https://www.fda.gov/medical-devices/reprocessing-reusable-medical-devices/what-are-reusable-medical-devices. (Accessed 14 May 2024).

Center for Devices and Radiological Health, 2020. Reprocessing Medical Devices in Health Care Settings: Validation Methods and Labeling. FDA [Internet]. https://www.fda.gov/regulatory-information/search-fda-guidance-documents/reprocessing-medical-devices-health-care-settings-validation-methods-and-labeling. (Accessed 7 August 2024).

Center for Devices and Radiological Health, 2024. Overview of Device Regulation [Internet]. FDA. FDA. https://www.fda.gov/medical-devices/device-advice-comprehensive-regulatory-assistance/overview-device-regulation. (Accessed 14 May 2024).

Center for Food Safety and Applied Nutrition, 2024. Guidance for industry: use of recycled plastics in food packaging. Chemistry Considerations) [Internet]. FDA. https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-use-recycled-plastics-food-packaging-chemistry-considerations. (Accessed 14 May 2024).

Chang, D.F., Hurley, N., Mamalis, N., Whitman, J., 2018. Evaluation of ophthalmic surgical instrument sterility using short-cycle sterilization for sequential same-day use. Ophthalmology 125 (9), 1320–1324.

Directive 2008/98/EC of the European Parliament and of the council of 19 November 2008 on waste and repealing certain directives (text with EEA relevance) [internet]. Available from: http://data.europa.eu/eli/dir/2008/98/2018-07-05/eng.

Dong, H., Xue, M., Xiao, Y., Liu, Y., 2021. Do carbon emissions impact the health of residents? Considering China's industrialization and urbanization. Sci. Total Environ. 758, 143688.

Eckelman, M.J., Sherman, J., 2016. Environmental impacts of the U.S. health care system and effects on public health. PLoS One 11 (6), e0157014.

Eckelman, M.J., Huang, K., Lagasse, R., Senay, E., Dubrow, R., Sherman, J.D., 2020. Health care pollution and public health damage in the United States: an update. Health Aff. 39 (12), 2071–2079.

Ellen MacArthur Foundation, 2019. The butterfly diagram: visualising the circular economy [Internet]. https://ellenmacarthurfoundation.org/circular-economy-diagram. (Accessed 4 August 2023).

EllenMacArthur Foundation, 2022. The biological cycle of the butterfly diagram [Internet]. https://www.ellenmacarthurfoundation.org/articles/the-biological-cycle-of-the-butterfly-diagram. (Accessed 22 May 2024).

EllenMacArthur Foundation. The circular economy glossary [Internet]. https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/glossary. (Accessed 14 May 2024).

EllenMacArthur Foundation. Compostable, biodegradable, and bio-based plastic – what's the difference? [Internet]. https://www.ellenmacarthurfoundation.org/compostable-biodegradable-and-bio-based-plastic-whats-the-difference. (Accessed 14 May 2024).

Eppler, M.J., Bresciani, S., 2013. Visualization in management: from communication to collaboration. A response to Zhang. J. Vis. Lang. Comput. 24 (2), 146–149.

FDA, 2024. Remanufacturing and servicing medical devices. https://www.fda.gov/medical-devices/quality-and-compliance-medical-devices/remanufacturing-and-servicing-medical-devices. (Accessed 14 May 2024).

Hoveling, T., Nijdam, A., Monincx, M., Faludi, J., Bakker, C., 2024a. Circular economy for medical devices: barriers, opportunities and best practices from a design perspective. Nat Resour Conserv Res 208.

Hoveling, T., Jin, Y., Faludi, J., Bakker, C., 2024b. Redesigning health devices for the circular economy: a case study on smart pillboxes. In: 2024 Electronics Goes Green 2024+ (EGG), pp. 1–12 [Internet]. https://ieeexplore.ieee.org/document/10631266. (Accessed 30 September 2024).

Kandasamy, J., Kinare, Y.P., Pawar, M.T., Majumdar, A.K.e.k.V., Agrawal, R., 2022. Circular economy adoption challenges in medical waste management for sustainable development: an empirical study. Sustain. Dev. 30 (5), 958–975.

Kane, G.M., Bakker, C.A., Balkenende, A.R., 2018. Towards design strategies for circular medical products. Resour. Conserv. Recycl. 135, 38–47.

Linstone, H.A., Turoff, M., 1975. Delphi Method: Techniques and Applications, p. 621. Reading, Mass.

MacNeill, A.J., Hopf, H., Khanuja, A., Alizamir, S., Bilec, M., Eckelman, M.J., et al., 2020. Transforming the medical device industry: road map to A circular economy. Health Aff Proj Hope 39 (12), 2088–2097.

Mahajan, V., 1976. Review of the Delphi method: techniques and applications. J. Mark. Res. 13 (3), 317–318.

McGain, F., Muret, J., Lawson, C., Sherman, J.D., 2020. Environmental sustainability in anaesthesia and critical care. BJA Br J Anaesth 125 (5), 680–692.

MDR-EU 2017/745. OJ L Apr 5, 2017 [Internet]. http://data.europa.eu/eli/reg/2017/745/oj/eng.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., PRISMA Group, 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 6 (7), e1000097.

Peters, A., Palomo, R., Ney, H., Lotfinejad, N., Zingg, W., Parneix, P., et al., 2021. The COVID-19 pandemic and N95 masks: reusability and decontamination methods. Antimicrob. Resist. Infect. Control 10 (1), 83.

Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular economy: measuring innovation in the product chain [Internet]. https://www.pbl.nl/sites/default/files/downloads/pbl-2016-circular-economy-measuring-innovation-in-product-chains-2544.pdf. (Accessed 4 August 2023).

Rethlefsen, M.L., Kirtley, S., Waffenschmidt, S., Ayala, A.P., Moher, D., Page, M.J., et al., 2021. PRISMA-S: an extension to the PRISMA statement for reporting literature searches in systematic reviews. Syst. Rev. 10 (1), 39.

Rodríguez-Jiménez, L., Romero-Martín, M., Spruell, T., Steley, Z., Gómez-Salgado, J., 2023. The carbon footprint of healthcare settings: a systematic review. J. Adv. Nurs. 79 (8), 2830–2844.

Sherman, J.D., Thiel, C., MacNeill, A., Eckelman, M.J., Dubrow, R., Hopf, H., et al., 2020. The green print: advancement of environmental sustainability in healthcare. Resour. Conserv. Recycl. 161, 104882.

Toomey, E.C., Conway, Y., Burton, C., Smith, S., Smalle, M., Chan, X.S., et al., 2021. Extended use or reuse of single-use surgical masks and filtering face-piece respirators during the coronavirus disease 2019 (COVID-19) pandemic: a rapid systematic review. Infect. Control Hosp. Epidemiol. 42 (1), 75–83.

Uiterkamp, A.J.M.S., Vlek, C., 2007. Practice and outcomes of multidisciplinary research for environmental sustainability. J. Soc. Issues 63 (1), 175–197.

United Nations Environment Programme, International Resource Panel, 2018. Re-defining value: the manufacturing revolution - remanufacturing, refurbishment, repair and direct reuse in the circular economy [Internet]. https://wedocs.unep.org/xmlui/handle/20.500.11822/31612. (Accessed 17 July 2024).

Waste framework directive - european commission [Internet]. https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en. (Accessed 13 May 2024).

World Economic Forum, 2024. Quantifying the impact of climate change on human health [Internet]. https://www.weforum.org/publications/quantifying-the-impact-of-climate-change-on-human-health/. (Accessed 6 November 2024).