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Review

How Can We Potentially Improve Medical Device Reuse, Recycling and Waste Management in Healthcare for a More Sustainable Future?

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Abstract: The supply of safe medical devices is of critical importance; however, many devices are increasing in complexity to reflect patient needs and for regulatory compliance. Single use devices (SUDs) have been extensively used in healthcare for various reasons including user convenience and perception of higher material quality, enhanced safety, and better mitigation of patient risk for device-associated infections. However, where appropriate, use of cleaned and processed medical devices are equally effective to that of using SUDs. Use of disposables has created considerable medical waste management issues globally. Consequently, this perspective review paper addresses key initiatives and recommendations for potentially improving a culture of medical device reuse and recycling in healthcare ranging from meeting scalability and predictability in supply chain to promoting green design thinking and regulation across micro, meso and macro levels of stakeholder engagement. Building such a comprehensive ecosystem, addressing core responsibilities, resource allocation, sustainable safe handling, segregation and disposal of medical device waste is likely to a long-term process, sustained by gradual incremental improvements and by increased stakeholder engagements. This integrated approach is likely to be supported and enabled by effective tailored strategies and systems, along with strong oversight and regulation, with the ultimate goal of informing national and international appropriate standards.

Keywords: medical devices; reuse; sustainability; resource management; circularity; patient safety

1. Introduction

The COVID-19 pandemic has stimulated an interest in sustainability practices for effective medical waste management such as triggering the safe recycling and reuse of materials from used personal and protective equipment [1–4]. Medical devices are manufactured as single-use devices (SUDs, such as syringes that are subject to industrial terminal sterilization modalities), or for reuse purposes (such as endoscopes that are typically processed in sterile services departments at healthcare facilities) [5]. The extent of medical waste generated globally arising for used or unused SUDs in healthcare is staggering [3,6]. Of the total amount of waste generated by healthcare activities, approximately 85% is general, non-hazardous waste [4]. For example, every year an "estimated 16 billion injections are administered worldwide; but, not all the needles and syringes are properly disposed of afterwards. Additionally, open burning and low-temperature incineration of health care wastes can, under some circumstances, result in the emission of dioxins, furans and particulate matter" [6]. It is apparent that appropriate measures to ensure the safe and environmentally sound management of healthcare waste are met to

prevent adverse health and environmental impacts from such waste including the unintended release of chemicals or biological hazards posing health risks [6] to disruption of fragile ecosystems due to accumulation of single-use plastics [7]. Thus, minimization of healthcare waste should be a priority where the potential environmental and climate impacts of inappropriately treated and disposal of such waste is considerable. For example, disposal of untreated health care wastes in landfills can lead to the contamination of drinking, surface, and ground waters if those landfills are not properly constructed [6]. Additionally, the WHO [6] recommends that waste minimization actions include green procurement and selecting products where shipping is minimized and with less and ecological packaging, switching to reusables when safe and viable, and recycling common items including plastic, paper and cardboard.

Recently, there has been an increased interest in the sustainable management of waste streams in adjacent industries such as for agri-food under the bioeconomy theme that can potentially inform circular practices for medtech sector [8]. The bioeconomy is the knowledge-based production and use of biological resources to provide products, processes and services in all economic sectors. However, with the exception of a limited number of research and desk-based literature studies [9], there appears to be a marked knowledge gap in tailored strategic polices to deal with safe medical device waste reuse that can inform viable solutions for business propositions. In general, development of effective bioeconomy frameworks has been held back by regulatory shortcomings, which includes the absence of appropriate pilot or commercial demonstration facilities at scale for companies that meets tangible end-user needs and mitigates against technical and economic uncertainties [8]. Additionally, the lack of predictability and absence of consensus on appropriate key performance measurement indicators for guiding, monitoring, separating, treating and regulating waste streams adds to this uncertainty or risk for investors and for regulators [8]. Hoveling et al. [9] reported that transitioning of medical devices towards a circular economy involves practices such as reuse, remanufacturing and recycling. These authors noted that although SUDs may minimize cross-contamination risks and increase manufacturers' profit, e-waste is one of the fastest-growing types of waste and awareness about this in healthcare is low. The healthcare industry is becoming increasing mindful of the need for practices, procedures, and devices that fit in a circular economy and are environmentally sustainable [10,11]. Hoveling et al. [9] revealed that of their inventory of best practices, only 346 of 1400 medical devices implemented more than one circular strategy. Moreover, it was particularly noteworthy, but not unexpected, that the fundamental recycle strategy was scarcely found in medical device design. Additionally, finding good circular examples for medical devices proved difficult where barriers were evident across six categories, namely, safety, systemic, regulatory, financial, technological and social. For example, some devices were thrown into the medical waste bin 'just to be safe', even thought they were not contaminated.

The supply of safe and effective medical devices to meet the diverse needs of patients is of parament importance [12]. Surgical site infections can occur due to environmental and skin surface contamination of single use devices (such as by catherization) [13,14]. Additionally, reusable medical devices that have not met appropriate cleaning or processing expectations can lead to patient infection in healthcare [15,16], which can be potentially attributed in part to increased complexity of design features making it challenging to effectively clean and process for patient safety [17]. This increased complexity in reusable medical device features reflects the number of stages described in manufacturer's instructions for use (IFUs) for end-to-end processing, which typically reflects patient clinical needs and regulatory compliance [12]. The risk of a patient succumbing to a hospital-acquired infection (HAI) post a clinical investigation or procedure can be mitigated by effective device cleaning and processing [17].

Medical devices are defined in part as instruments, machines or implants intended by the manufacturer to be used for human beings for a medical purpose [18]. Medical devices can be classified as either single-use or reusable [19]. A single-use medical device (SUD) is defined as a device "labelled or intended for use on one individual during a single procedure." In contrast, a reusable medical device is one "designated or intended by the manufacturer as suitable for processing and reuse" [18]. Devices once considered reusable, such as surgical drapes, are now best practice to be disposed of after a single patient use that are commonly referred to as 'single use devices or (SUDs)' [20]. The focus on patient safety and meeting regulatory standards has encouraged healthcare providers to invest in high-quality disposable devices [21]. This focus has influenced growth in medtech sector and has informed a critical pipeline of new innovation that includes use of artificial intelligence (AI)-enabled devices [5,22–26].

The increasing concern over transmissible diseases, most notably HIV/AIDs, and infectious agents such as prions, has influenced the augmented investment in SUDs by healthcare facilities globally [27]. Over time, an increased trend toward disposable device use over durable devices has occurred in healthcare that has been attributed to several contributing factors including user convenience, the perception of higher material quality, enhanced safety, and better mitigation of patient risk for device-associated infections [25]. Additionally, disposable devices are often viewed as more cost-effective, contributing to their widespread adoption [19]. For example,

Greene et al. [27] noted that the reliance on SUDs emerged from concerns over safety (e.g., prion-contaminated materials used on vulnerable patients) and efficiency, which has in turn created challenges in addressing supply chain shortages. Most of the medical devices used in the intensive care unit (ICU) are primarily single use where ICU carriers a large environmental burden [28]. These authors reported that extending routine replacement of plastic line sets from 4 to 7 days that belong to intravenous administration or invasive monitoring can lower waste from single-use plastics in ICU. This safe practice in term of catheter related-bloodstream infections (CRBSI) and durability, reduced plastic waste of this category by 62% and saved in materials and staff costs. Specifically, these researchers reported that in total 1221 patients were admitted to ICU; 636 in the pre-intervention period and 585 in the post-intervention period. There was a reduction of 881 replacement sets, 182 kg of waste and 96 nursing hours in 2022. There was no difference in CRBSI incidence. Moreover, such research highlights significant opportunities for developing strategic polices to advance green healthcare practices, such as by creating greater end-user awareness, by staffing and training, and by promoting sustainability practices that will require both investment and management. The scope for improvements in design innovation for medical device reuse remains apparent. For example, the Sedgwick's 2025 US State of the National Recall Index' report [29] noted that medical device sector documented an 8.6% increase in recall events, reaching 1059 events in 2024. Additionally, the US FDA posted 35,039 adverse event reports related to outbreaks, injuries and reprocessing failures associated with medical devices in 2024 [30].

Several researchers have voiced concern about the potential impact of disposable healthcare supplies on our fragile environment [19,31–34]. The Environmental Protection Agency [35] reported on guidance and tips from a waste prevention programme under topic 'GreenHealthcare) for Irish healthcare facilities. The lack of appropriate waste management for SUDs during the COVID-19 pandemic has also highlighted the importance on addressing sustainability, such as for dealing with the unprecedented shortage in supply chain of face masks and the widespread increased use of PPE [36]. For example, for a small nation of 5.5 million people, an astronomical €915 million was spent by Ireland to obtain PPE including face masks in 2020 to fight against COVID-19 [36,37]. Additionally, emergency funding from Irish government funded strategies to address knowledge gaps for meeting appropriate responses to COVID-19 pandemic; but, the effective decontamination and potential reuse of PPE to address sustainable waste management was not foreseen nor considered. As this pandemic progressed, different modalities were reported to be effective for safe treatment of PPE for reuse under Emergency Use Authorization [38] including research to improve sustainable waste management [39].

Such a scenario is now influencing how we can avoid, reduce, reuse, or recycle medical device waste that is reflected in several emerging 'green' initiatives in healthcare [40,41]. Emerging technologies under Irelands' Disruptive Innovation Fund [42] are also focusing on improved sustainability in healthcare that considers the bioeconomy, for example 'Solascope' consortium is addressing a novel self-sterilizing, panaramic endoscope designed for and enabling the circular economy for medical devices. Additionally, Health Innovation Hub Ireland [43], with the Health Service Executive and the Irish College of GPs have recently funded the first 'GreenTech in Healthcare' to address sustainable medical devices, transitioning to circular economy model, reducing environmental footprint and medical waste management [43]. For example, the company Aerogen pitched for a multi-disciplinary project focusing on sustainable Solo Nebuliser products; the company Vanguard AG is addressing a solution for remanufacturing of single-use medical devices; the start-up company HaPPE proposes a solution for a full cycle bio-digestion system addressing sustainable on site healthcare waste management including decontamination for compostable PPE; EccoSpray company will develop an eco-friendly alternative to traditional ultrasound gels to measure sustainability, waste reduction and efficiency benefits; a consortium of Irish companies (Offerre, Envetec, DeltaQ, and Enva) will develop a multi-faceted solution focusing on medical waste treatment and recovery; and the company MedfirstSupplies pitched for a closed, sealed cabinet system that automates manual cleaning of reusable medical devices with a focus on combed use of sodium biocarbonate with compressed air for effective pre-cleaning. Appropriate pilot testing and verification facilities will be required in Irish healthcare facilities to test and demonstrate these potential GreenTech solutions.

Thus, the aim of this perspective review is to discuss key contributing factors that potentially influence an increased culture of reuse of medical devices and sustainable waste management for improved circularity.

2. Method

A PRISMA style approach was used to screen and review published papers in PubMed databased over the period Jan 2010 to April 2025. The PRISMA statement (Preferred Reporting Items for Systematic Reviews and Meta Analysis) helps authors to report a wide array of systematic reviews to assess the benefits and harm of an intervention [5]. Key words (and combinations thereof) used in this review were medical device waste (MDW,

n = 21,345), reuse (n = 40,254), sustainability (SUSTAIN, n = 488,245), decontamination (DECON, n = 12,801), recycling (n = 68,376), life cycle assessment (LCA, n = 9161), single-use devices (SUDs, n = 158,183), MDW + Reuse (n = 1560), MDW + Recycling (n = 233), MDW + Recycling + regulatory (n = 10), MDW + DECON (n = 214), SUDs + LCA (50). Inclusion criteria included key words that addressed reuse, recycling, decontamination of medical device waste and its' regulation. Excluded papers included for example reported studies on telemedicine treatment, lead batteries, membrane processes, winery waste, drainage systems, semi-conductors, photo-electric fenton process, substance use disorders, e-waste, renewable fiberboards, xeno-keratographs, tuberculosis treatment, cheek reconstruction, imaging disk-based live cell array.

3. Results and Discussion

3.1. Medical Device Reuse

Safe and effective processing is defined as the process to prepare a device, instrument, or piece of equipment for reuse by any or a combination of the following processes; point-of-use treatment, cleaning, disinfection, sterilization, and rinsing at appropriate stages [44], and is of critical importance for patient care [12]. The responsibility for the processing of reusable medical devices falls to healthcare facilities and has traditionally been conducted by a central sterile processing department within a hospital [17]. Sterile processing is a department that operates without generating profit, so it often faces budget limitations and may have a team with varying levels of formal education [20]. This situation has presented challenges, as reusable medical devices have become increasingly complex over the decades to meet evolving medical and patient needs [5]. Greene et al. [27] noted "by the end of the 1970s innovation in disposability eclipsed innovation of reliable infrastructure for sterilization—and indeed could allow hospital managers to replace skilled workers with supply chains".

The last 60 years have been focused on establishing best practices for standardization and decreasing the risk of a hospital acquired infection (HAI) that includes innovation in processing and sterility assurance [21]. Methods to communicate patient risk were established to facilitate the communication between medical device manufactures who provide the instructions for use and the healthcare personnel responsible for executing those instructions [17,20]. Earl Spaulding developed a classification for the microbial reduction requirements of a reusable medical device based on the patient use [45]. The relevance of this system is still applicable today as long as the base assumption of device cleanliness has been established [4]. However, there is evidence of healthcare outbreaks attributed to reusable medical devices where ineffective cleaning has been reported [12,46]. Evidence demonstrated by [20] suggests that ineffective cleaning may be attributed to difficult to clean features and improper training during cleaning execution that impacts the ability to subsequently disinfect and/or sterilize. There is a default culture of reliance in healthcare that sterilization will effectively treat devices even if not properly cleaned, which is not the case [25]. The role of bespoke staff training to inform emerging developments in healthcare is critically important that can be informed by digital technologies such as use of extended reality [17,26,47].

Ensuring effective interplay between manufacturers' instructions for use (IFUs), healthcare facilities (appropriate equipment, training including interpreting IFUs for cleaning, disinfection, sterilization) and regulators (testing, verification, validation) for safely reprocessing medical devices is challenging [25]). It is recognized that manufacturers' IFUs can be overly complicated for complex reusable medical devices to meet patient and regulatory needs [25]. This has significant implications for sterile processing departments, which may vary greatly in terms of the infrastructure and equipment available—both regionally and internationally—required to align with the manufacturer's IFUs [25].

There are reports of patient infections and outbreaks in processed medical devices that have occurred despite no documented evidence of device damage nor process failure, which highlights gaps between modern-day manufacturer's IFUs and the ability of healthcare facilities to implement appropriate cleaning and processing based on interpretation of IFUs or due to safe clinical/surgical use [25]. It is appreciated that many of these device-related infections can be attributed to intrinsic or extrinsic infections risks such as natural flora contamination of single-use devices [5]. Healthcare device-associated infections have been reported due to lapses in device decontamination such as with patient-ready laryngoscopes, gastroscopes and duodenoscopes that have complex design with internal lumens and multiple channels [48]. Davis [49] hypothesized that complex device designs with compound hinges, gaps, channels and lumens can also result in bioburden accumulation along with development of biofilms harbouring problematical microorganisms. Okamato et al. [50] noted errors in 27.7% of duodenoscope processing procedures and recommended increased awareness of IFUs along with implementing appropriate training for healthcare staff. When device reprocessing is conducted correctly, a reprocessed device can be just as safe, effective, and cost-efficient as a single-use device while significantly reducing environmental waste [51].

Embracing effective reprocessing practices not only protects patient health but also supports a more sustainable healthcare system by minimizing the impact of medical waste on the environment [4].

The WHO [6] noted that "Incineration of waste is widely practiced; but, inadequate incineration or the incineration of unsuitable materials results in the release of pollutants into the air and in the generation of ash residue. Only modern incinerators operating at 850–1100 °C and fitted with special gas-cleaning equipment are able to comply with the international emission standards for dioxins and furans. Alternatives to incineration such as autoclaving, microwaving, steam treatment integrated with internal mixing, which minimize the formation and release of chemicals or hazardous emissions should be given consideration in settings where there are sufficient resources to operate and maintain such systems and dispose of the treated waste". Examples of established and emerging activities addressing the sustainable reuse and disposable of medical devices including waste management considerations are described in Table 1. It is apparent from the findings presented in existing published studies that there are significant merits for improving a culture of medical device reuse for planetary health outcomes. There are an increasing number of life cycle assessment (LCA) studies comparing SUDs to that of similar multi-use medical devices where the latter reusable option consistently supports better performance on key indicators ranging from lifetime carbon footprint to waste disposal costs (Table 1). However, there is a marked gap in focused evidence-based studies addressing logistics in supply chain for managing the scaling of used medical device and their recyclable components (where appropriate) for waste management over a timely manner, along with promoting an awareness of reuse with stakeholders for prioritizing these circularity activities. Additionally, there is also evidence of inter-study heterogeneity and method quality variances that makes comparatives between studies difficult to discern (Table 1); thus, supporting the goal of garnering consensus on developing appropriate standard methods with stakeholders for enabling the coordinated evolution of 'regulated green-thinking' of medical device waste and resource management globally.

Table 1. Established and emerging themes in published literature (Jan 2010 to April 2025) addressing sustainable reuse and disposable medical devices, waste management and circularity.

Theme	Description	Refs.
LCA	➢ Systematic review (2005–2024) compares environmental footprint of single-use vs. multi-use instruments for minimally invasive procedures ➢ Instruments studies include laproscopy systems, endoscopes, cystoscopes, bronchoscopes, duodenscopes, ureteroscopes ➢ Six studies revealed that SUDs had higher environ footprint	Martins et al., [52]
LCA	➢ Reusable surgical cotton caps reduced CO_2 equivalent (eq) emissions by 79% compared to disposable bouffant caps. ➢ Given lack of evidence suggesting superior choice for surgical infection site infection—cotton caps recommended to reduce environmental impact ➢ Findings limited by inter-study heterogeneity and method quality ➢ Need for employing standard methodologies to address interplay in environ impact and operational factors (workflow efficiency, cost-benefit ratio) for decision making	Donahue et al. [53]
LCA, material composition, carbon footprint & sustainability	➢ Compared single use (SUDs) and reusable duodenoscopes (RUDs) ➢ RUDS with lifetime carbon footprint 62 to 82 times lower that universal use of SUDs and 10 times lower than occasional use (152 vs. 1477–1677 Kg CO_2 eq per endoscope) ➢ End-of-life incineration of SUDS greatest environ contribtor	López-Muñoz et al., [54]
LCA incorporating Planetary Health principles in healthcare practices	➢ Intra-institutional process of LCA for single-use and reusable ureterorenoscopes (fURS) to assess GHG emissions (CO_2-eq) generated across full life cycle of fURS including production, use-phase, reprocessing, maintenance and disposal. ➢ Single-use and reusable fURS generated 4.93 kG CO_2-eq and 1.24 kg CO_2-eq resp. ➢ SUDs higher environ and health impacts. ➢ Production and processing stages identified as having greatest environmental and health impacts	Thone et al., [55]
LCA	➢ Reusable pulse oximeters generated fewer GHG emissions per day of usage that their disposable counterparts ➢ Pulsed oximeter used in emergency care globally, thus carbon emissions could be reduced if EDs used reusables	Duffy et al., [56]

Table 1. *Cont.*

Theme	Description	Refs.
LCA	➢ Comparative LCA between SUDs and reprocessed intermittent pneumonic compression (IPC) sleeves ➢ LCA performed as per ISO 14044 using Environ Footprint 3.0 ➢ Data obtained in cooperation with IPC sleeve manufacturers ➢ EO emissions during processing, transport and waste reduction on hospital disposal cost was calculated ➢ Reprocess IPC sleeves reduced CO_2 footprint by 40% ➢ Waste disposal costs were reduced by 90% for reuse option	Lichtnegger et al., [57]
Sustainability and climate change	➢ Balance optimum care (patient safety) with use of disposable endcaps and different HLD techniques for GI endoscopy that is high waste generator in healthcare	Nabi et al. [58]
LCA and life cycle costing (LCC) methods Device procurement	➢ Comparing reusable and disposable laryngoscopes ➢ SUD plastic handle generated 16–18 times more life cycle CO_2 equivalents than low level disinfection of reusable steel handle ➢ Extrapolated over 1 yr (60,000 intubations), estimated costs increased between \$495k to \$604k for SUD handles and between \$180k to \$265k for SUD blades, compared to reusables, depending on cleaning scenario and assuming 4k (rated) uses.	Sherman et al., [59]
LCA	➢ LCA of hysterectomy in the United States of America (USA) ➢ Data collected from 62 cases of hysterectomy ➢ Major sources of environ emissions include production of disposable materials and single-use surgical devices, energy used in heating, ventilation, air conditions, anaesthesia gases. ➢ Healthcare industry can strategically optimize sustainability by scientifically evaluating emissions	Thiel et al. [60]
LCA	➢ Single-use dental examination kit poses greater ecological and human health threat than reusable examination kits.	Byrne et al. [61]
Costs and Safety	➢ Systematic review of reusable vs. disposable Laparoscopic instruments (Medline/EMBASE databases Jan 2000 to May 2015) ➢ Theoretical advantages of SUD instruments in quality, safety, sterility, ease of use and patient outcomes rarely examined ➢ Cost saving methods, eco-friendly methods, global operative costs, sterilization methods & quality assurance systems vary greatly making it difficult to compare between SUDs and reusable	Siu et al. [62]
Reuse of SUDS/Patient safety	➢ Reuse of SUDs in Endourology—a scoping review (1970 to 2023) ➢ While reuse of medical equipment can contribute to reduction in toxic biodegradable waste, there is scarcity of data on safety and efficacy of reused SUDs (practice must be regulated properly)	Ghorai and Kumar [63]
COVID-19 trigger	➢ Stimulated interest in 'green thinking' brought on by COVID-19 supply chain and build-up of medical waste—such as modelling respirator use strategies to reduce cost and waste	Chu et al. [64]
Supply chain	➢ 20,049 inhalers were returned via post saving equivalent of 119.3 tonnes of CO2 emissions via recycling schemes	Murphy et al., [65]
Innovation	➢ Application potential for use of shredded waste nitrile glove (PPE) fibers in sustainable cement-based materials	Tan et al., [66]

ED (emergency department), LCA (Life cycle assessment), SUDs (single-use devices), RUDs (reusable devices), GHG (greenhouse gas); EO (ethylene Oxide); GI (gastrointestinal); HLD (high level disinfection).

3.2. Medical Device Reuse and Recycling—Quo Vadis?

Single-use medical devices were not originally designed for processing or reuse [1,2]. There is a need to achieve an appropriate business model for companies to collect medical waste, to reprocess devices, and to resell them back to healthcare facilities [67]. These companies take the legal liability for the devices they collect and in essence become the manufacturer. Within the US, this is a regulated process, where the company must demonstrate that when they reprocess the SUD, it is equivalent in safety and performance to what was demonstrated by the original equipment manufacturer (OEM) [67]. In other parts of the world, specifically low-income countries, reprocessing of single-use devices may also take place as a cost-saving measure; but, it is often performed within the healthcare facility itself [25]. This unvalidated and unregulated process can pose significant risks to patient safety, as improper cleaning, sterilization, and handling of devices may lead to infections or device failures.

Furthermore, the lack of standardized protocols and oversight increases the likelihood of reprocessed devices not meeting the required safety and performance standards [68].

Emergency use protocols for the reprocessing of single use devices gave an increased awareness to infection prevention and the over-reliance on a global supply chain during COVID-19 pandemic [1]. When properly regulated, the risks of reprocessing a single-use device can be weighed against both the potential harm to individual patients and the environmental impact of medical waste [69]. It is appreciated that the next level of medical device recycling is on the horizon [41]. Complex medical devices of the future are already proving challenging that includes the need to consider automation and regulated AI-enabled devices [25]. These devices are complex with intricate components and are consequently expensive. Not all the components in devices will be compatible with all required processing steps to ready them safe for subsequent patient use [25]. A single-use medical device with a hybrid design might include a surgical tool, such as a laparoscopic instrument, where certain components are designed to be reprocessed and reused, while others must be replaced before each use [4,17]. Unlocking future next-generation design for sustainable devices that reduce waste while ensuring safety and efficacy for each procedure will be strategically important (Tables 1 and 2). Such innovation and their regulation will also be informed by Lean 6 sigma practice [70].

Table 2. Governance, educational, societal and regulatory themes in published literature (Jan 2010 to April 2025) influencing sustainable use medical devices and circular waste management.

Theme	Description	Refs.
Corporate Social Responsibility (CSR)	➢ Green financing, carbon performance and CSR, Green Credit policy can boost carbon performance in carbon intensive companies ➢ Policy failed to stimulate technological innovation,	Chen et al. [71]
Educational Intervention	➢ Operating room waste reduction ➢ Reduction of waste and cost savings of opened and unused endotracheal (ET) tubes, disposable laryngoscope suppliers in operating room (OR) environment ➢ Weekly average waste reduction of ET tubes reduced by 62.6% and laryngoscope blades by 54.7% highlighting benefit of education intervention	Denny et al. [72]
Education (HCW and Patient)	➢ Healthcare/rehabilitation providers to be trained in environmentally sustainable practices for durable medical equipment (DME) reuse and recycling ➢ Patients to be educated on how to sustainably manage unwanted DME ➢ Disconnect between practices to prevent DME waste at healthcare level and clinical decision making for patient care	Ordway et al. [73].
Education and Advocacy, Research translation and LCAs	➢ Sustainability research in anaesthesia and critical care. ➢ Atmospheric chemistry of anaesthesia gases (relative global warming and waste treatments) ➢ LCAs with practical outcomes e.g., carbon footprint of SUDs vs reusable anaesthesia equipment (drug trays, laryngoscope blades etc), or carbon footprint of treating an ICU patient with septic shock ➢ Avoid, reduce, reuse, recycle, reprocess explored.	McGain et al. [74]
Education and Training	➢ Use of real-time immersive digital training and educational technologies to improve patient safety during the processing of reusable medical devices	Kremer et al. [20]
Perioperative waste management	➢ Nurses and can moderate negative environmental effects by promoting reduction, recycling and reuse of materials including procedural changes	Lausten [75]
Ethical and Sustainable future for hospitals	➢ Decreasing medical waste in paediatric intensive care unit in USA ➢ ICU major contributor of waste production due to patient complexity/extensive use, cleaning practices, pre-emptive supplies—HCWs collected unused medical supplies destined to be discarded over 3 one-week periods ➢ Must consider all implications on daily decisions	Ghersin et al., [76]
Environment, Societal & Governance Aspects	➢ Healthcare operators/managers to match medical devices (and their components) with appropriate waste management ➢ Limited quantity of waste, and reduced risks for adverse reaction have positive impact on environ pollution and costs sustained by healthcare institutions and communities.	Boccato and Vienken [77]

Table 2. *Cont.*

Theme	Description	Refs.
Design and holistic thinking	➢ Sustainability in medical devices should also address quality of design, biodegradability, and inbuild performance service for patients, healthcare professionals and providers. ➢ Consider polymer specification and performance properties (chemical modification/degradation) during waste disposal ➢ Holistic and interdisciplinarity approach to MD sustainability ➢ Device features design thinking for future medical device reuse, ease of cleaning, processing and patient safety ➢ A new quantitative method for determining patient risk for reusable medical device categorization based on using and interpreting Kremer's cleaning classification system	Vienken and Boccato [78] Kremer et al. [17] Kremer et al. [20]
Deep Learning and automated detection and classification of medical waste	➢ Deep learning (DL) approach to medical waste identification and classification ➢ DL is most popular technique in image classification; but, it needs large amounts of data that otherwise limits its use ➢ ResNneXt proposed as suitable deep neural network for practical implementation—3480 images analysed where 8 kinds of waste were correctly identified (97.5%)	Zhou et al., [79]
Machine Learning (ML)	➢ Predicting medical waste generation and associated factors using ML in Kingdom of Bahrain	Al-Omran and Khan [80]

DL (deep learning); PPE (personal and protective equipment), ET (endotracheal), LCA (life cycle assessment); HCW (healthcare worker), DME (durable medical equipment); ICU (intensive care unit); MD (medical device); CSR (Corporate Social Responsibility); ML (Machine Learning); OR (operating room).

3.3. Guiding Practices to Meet Circularity Needs and Expectations for Medical Device Waste

The medical device manufacturer is responsible for properly labelling and providing instructions for use (IFU) to ensure correct application by healthcare professionals, whether the device is single-use or reusable [26]. This enables healthcare facilities to understand how to handle the device post-use. It could be argued that the manufacturer should also be responsible for the environmental impact of the devices they sell within the healthcare industry. Design changes should incorporate device features and materials that foster 'green' sustainability as well as meeting safety and efficacy claims. Waste produced should be minimized so as not to impact other portions of the globe. The ability to reuse all or part of a medical device would promote a circular rather than a linear termination (such as land fill, or incineration) [81].

Additional safeguards based on scientific evidence within the device processing steps will continue to build confidence from the medical device community. Kremer et al. [51] conducted over 160 validations from 23 device features used in medical devices to understanding potential relationship between features and patient usage and risk to deliver the Kremer cleaning classification as a complement to Spaulding's microbial reduction classification. This approach will inform simplification of device features used in medical devices and create opportunities for introducing appropriate materials (including biomaterials) more suitable for reuse. Healthcare facilities should urge medical device manufacturers to prioritize sustainability in their designs. Without customers holding companies accountable through purchasing decisions, meaningful change is unlikely to occur. By adopting this approach, healthcare facilities could significantly reduce waste while maintaining safety and effectiveness. However, transitioning from single-use to reusable devices requires careful consideration of factors such as cost-effectiveness, infection control protocols, and regulatory compliance. The decision to replace a single-use device with a reusable one should prioritize patient safety while also evaluating the overall environmental benefits [5]. Interestingly, life cycle assessment (LCA) environmental studies conducted thus far strongly advocate implementing reusable options over disposable counterparts for many types of medical devices that includes carbon footprint and energy [25]. McGain and McAlister [41] highlighted those reusable items were 300 times more environmentally sustainable than alternative disposables from review of published LCA studies. These authors advocated that "this is akin to adopting the reusable coffee cup concept over single-use-plastic disposables". Researchers have intimated the environmental and financial benefits of reusable devices over disposables [40,82].

Use of disposables commands a significant healthcare budget allocation where there is a concerted need to also address financial commitments to promote and manage reusable devices for sustainable practices. Rowan [5] noted the benefits of using a combinational Penta Helix Hub approach of stakeholders for co-creating solutions

for reuse of devices and their components including appropriate sustainable waste management. The concept of Penta Helix or Quintuple Helix have been widely discussed and used as frameworks in many researches in "relation of innovation or organizational innovation field. it is believed that if the Penta Helix stakeholders work together in synergy it will foster innovation and an innovation-based economy" [83]. The partnering with medical device industry will also potentially offset the lack of or misinterpretation of international standards by non-subject specific experts for developing new innovations and processes [84–86]), which can be facilitated through this collaborative Penta Helix multi-actor framework. Key indicative interdisciplinary activities supporting the concerted development of a green approach to medical device waste management through the Penta Helix Hub framework is described in Table 3. Additionally, established and emerging activities to promote greater reuse and recycling of medical device waste range from educational interventions for healthcare professionals and stakeholders to governance, ethical and societal advocacy aspects (Table 2). There is increasing interest in green financing and carbon performance including support under corporate social responsibility (CSR) for enabling more sustainable options for medical device waste reduction and recycling; however, this requires a holistic and interdisciplinary framework approach to delineating tangible measurable values including incentivising and rewarding early-adopters. Evolving such processes, such as through collaborative use of multi-actors under such a Penta Helix hub framework, will also inform appropriate consensus on international standards and its' regulation.

Hoveling et al. [9] identified barriers and opportunities to improve circular design of active medical devices that could be enabled thorough a Penta Helix hub collaborative approach. The authors noted circular practices that included eliminating the need for unsustainable devices (*reuse*), reducing energy consumption (*reduce*), offering multiple functions in one device (*rethink*), and eliminating electronic components without compromising functionality (*reduce*). Additionally, the authors were surprised that *rethink* emerged as the second most prevalent strategy, following *reuse*. Hoveling et al. [9] determined which devices had the highest circularity potential enabled by developing a circularity scoring method base on the hierarchy and the original definition of the R-strategies [87]. However, adoptions were applied to the definitions of circular strategies hierarchy by the authors, specifically:

- For *reuse*, the authors added the notion that the replacement device must not only be radically different; but, also more environmentally sustainable.
- They introduced *renew* (regenerate, compost, biodegrade) as an option for parts unsuitable for 'techno cycle strategies.
- They merged *refurbish* and *remanufacturing* despite distinct definitions, driven by identical processes due to the high-quality standards for medical devices.
- They merged *reuse* and *repair.* Whilst recognizing *repair* as a distinct R-strategy, they found repair and maintenance frequently mentioned without further clarification. They also consider maintenance to be an intrinsic part of reuse.

Current research on circularity in medical devices suggests that consensus must be reached on key performance and measurement parameters across all the R-strategies for advancing effective waste management globally, which will be enabled by using a combined Penta Helix Hub approach [5].

Thus, society needs to embrace and strategically implement sustainable 'green' practices that will introduce appropriate durable reuse options in healthcare. Significant advances have been made in our understanding of technical and procedural bottleneck areas for effective cleaning and processing [20] of reusable devices from a medical design feature and patient risk perspective. However, given the variability in manufacturer's IFUs and differences in healthcare facilities, there is a commensurate need to implement appropriate educational (including and immersive training) for implemented these green needs [26]. The future role of non-destructive device sampling [22,25] along with use of machine learning and modelling will also inform sustainability practices. Greene et al. [27] noted that transitioning to a more circular culture along with opting for investing in high quality reusable medical equipment may lead to lower healthcare costs that will also promote a more sustainable environment. However, this approach will require greater attention and investment to ensure that it is correctly and consistently managed. Interestingly, these authors reported that ca. 80% of healthcare industry's carbon footprint is attributed to production, transportation, use and disposable of single-use medical devices.

Table 3. Addressing medical device waste management opportunities and challenges through integrated access and use of a Penta Helix hub framework.

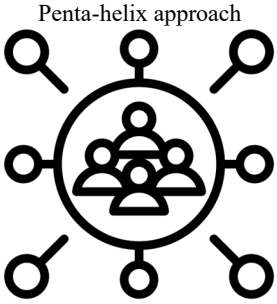
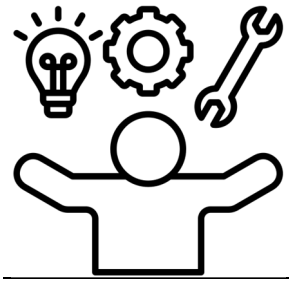
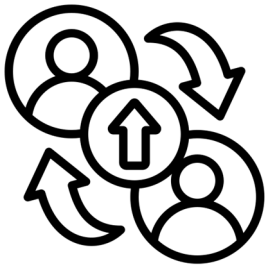
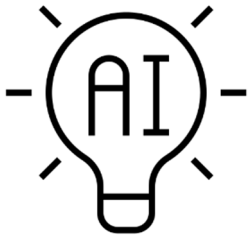
Activity	Description	Benefits	Example Refs.
Multi-actor integrated Penta-helix approach 	▪ Integrated academic, industry, policy (regulators), society via digitally enabled approach ▪ User interface for enabling policy ▪ Appoint expert HUB manager ▪ Step change physical infrastructure & support systems at scale ▪ Education, training	▪ Multi-actor (specialist) inputs—working with manufacturers (IFUs) ▪ Networking/conferencing ▪ Holistic problem solving ▪ Access to specialist equipment/staffing/mentors ▪ Clustering of resources ▪ De-risking and mitigation ▪ Consensus on tangible impact (KPIs) across micro, meso and macro tiers ▪ Ecosystem building for end-users including enterprise accelerator ▪ Keeping pace with standards and regulatory underpinning ▪ Pilot/demo testing including design and green thinking.	Rowan [5] Boccato and Vineken [77] Ghorai and Kumar [63] Thiel et al. [60] Sherman et al. [59] Chen et al. [71] McGain et al. [74] Rowan and Casey [88] Rowan [89]
Technical 	▪ Interdisciplinary expertise ▪ Enterprise training for scaling ▪ LCAs ▪ Standards development ▪ Digital tools (deep learning, automation)	▪ Testing and demonstration at scale (end-to-end) ▪ Ecosystem building, emissions and energy monitoring etc ▪ Ideation, eco-design thinking ▪ Appropriate IP management ▪ De risking and investing ▪ Eco-material Science, HLD, safe by new design thinking ▪ Digital transformation	Vineken and Boccato [77] Rowan 5] McGain et al. [74] Rowan [8]
Regulatory 	▪ Interface for informing strategic policies ▪ End-to-end engagement ▪ Transparency	▪ Consensus methodology deployed for demonstration ▪ Risk Management ▪ Builds partnerships with multi-actors enabling evidence-based data including digital needs ▪ Keeps pace with standards including appropriate AI ▪ Holistic safe approach to meeting needs (end-to-end)	WHO [6] Rowan [5]
Business, Engagement and Communication 	▪ Test the tech/test before invest ▪ Business model canvas, SWOT and accelerator ▪ Integrated ecosystem building ▪ IP Management ▪ Access to finance/ investments ▪ Tangible KPIs	▪ Financial viable product/value proposition (cost structures), green, CSR ▪ Providing key resources and expertise across TRLs ▪ Physical and virtual demo ▪ Networking key partnerships ▪ De-risking and optimized value stream ▪ Market research /needs analysis ▪ Grant and specialist ▪ Dissemination and communication channels	Siu et al. [63] Rowan, [5] Kremer et al. [20] Rowan and Casey [88] Rowan [8] Ofstead et al. [90]
Sustainability 	▪ Energy and GHG emission footprint (LCA) ▪ Technical, political, societal LCAs ▪ Carbon Credits ▪ Government investment	▪ Holistic approach (penta-helix) using multi-actors (experts) to innovation ▪ Efficient circular bioeconomy model (consensus/standard) ▪ End-to-end lifetime profiling ▪ Standards development ▪ Reward early adopters	Rowan [5] Donahue et al., [53] Thone et al., [55] Lichtnegger et al. [57] Siu et al. [62] Anukwonke et al. [91]

Table 3. *Cont.*

Activity	Description	Benefits	Example Refs.
Social & Citizen Sciences 	▪ Social marketing ▪ Social enterprises ▪ Society engagement and acceptance ▪ Outreach activities ▪ Citizen Science	▪ Promotes behaviour change ▪ Holistic approach to medical waste management ▪ Consensus and adoption of effective practices to initiatives (CSR) ▪ Long term viability where current and next-generation are guardians of fragile planetary health	Rowan, [89] McGain et al., [74] Rowan, [5] Chen et al., [71]
AI and Automation 	▪ Deep learning of data for waste and prioritizing ▪ Scaling supply chain for large data sets ▪ Modelling and validation ▪ Regulatory	▪ Efficiency in handling, segregation and disposal of medical waste ▪ Informing effective design and green thinking ▪ Holistic approach to complex issues using digital tools ▪ Informing and embracing standards/regulatory needs	Rowan [5] Zhou et al. [79] Al-Omran and Khan, [80]
Educational technologies & training 	▪ Bespoke training across activities and disciplines ▪ Facilitates mobility and upskilling ▪ Educational technologies (cognitive) blended with extended reality	▪ Training including next-gen of 'game-changers' ▪ Universal design by learning (UDL), Lean Six Sigma ▪ Enhanced Productivity/Efficiency ▪ Boost and improve collaboration for unlocking techno-societal solutions ▪ Consensus on measurable impact (KPIs) ▪ Sustainable practices	Lausten, [75] Ordway et al., [73]; McGain et al., [74]; Kremer et al., [20]; Rowan and Casey,[88] Rowan, [25] Denny et al., [72]

LCA (life cycle assessment), UDL (Universal design by learning), KPIs (key performance indicators), TRL (technology readiness level), IoT (internet of things); AI (artificial Intelligence).

Addressing new device design that limits or prevents occurrence of residual material on medical device surfaces is also important as this can offset increased risk for patients due to medical device malfunction, damage, and biocompatibility issues [20]. However, the challenges to visualize and appropriately meet these multi-factorial challenges are complex (design features, materials, sterilization, applications) that can be met by re-creating the physical item in a safe virtual world (digital twin) combining with using specialist virtual and augmented reality training, such as for modelling, simulating and predicting the effectiveness of cleaning and decontamination of devices in ICU facilities that includes opportunities for advancing 3D printed devices (extended reality). Recently, there has been a surge in interest in the use of virtual reality innovation for addressing pressing ICU and surgery applications [25]. Digital twins (DTs) and eXtended Reality (XR), referred to as "TwinXR", are exciting enabling technologies for advancing applied innovation in the Metaverse with potential to transform healthcare training and processing improving patient outcomes [92]. This approach offers opportunities for healthcare professionals to visualize medical device design and applicability from an integrated (entire) end-to-end process in a virtual world from the convenience of your computer that includes experiencing specialist real time training for use, development, application and validation. DTs enables a digital representation of its physical counterpart (medical device) that links digital data between the two for holistic design, inspection, monitoring and prediction of highly sophisticated processes [93], while XR encompassing Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) provides a commensurate combined real-to-virtual environment for medical team users to interface with machines for specialist applications. This combined TwinXR approach offers scalable and effective XR development that both demonstrates and unlocks opportunities for holistic interoperation of connected processes for user with stakeholders such as for advancing training and in-house practices in surgery (3 D printing) [94,95].

Kanschik et al. [96] reviewed 59 papers published on VR and AR use in intensive care medicine and concluded that these innovations can help ICU personnel train, plan and perform difficult procedures such as cardiopulmonary resuscitation, vascular punctures, endotracheal intubation, or percutaneous dilatational tracheostomy. This holistic approach allows for components that are not reusable to be replaced with more

sustainable (reuse) materials in the device, where appropriate. Another option is to use this approach to inform design of devices limiting single use parts, but where the majority of the device is deemed reusable. For example, using immersive technologies to understand applicability of cleaning classification combined with sterilization modalities based on design features, it will be possible for clinicians to advice companies on reusable devices that are also economically viable. Healthcare facilities should also be demanding medical devices manufacturers to produce medical devices that are sustainable that may influence short term profitability. Thereby, affecting change by leveraging purchasing power. A simple example are rigid containers that are just as effective as the blue wrap, but former as used less often, which would significantly reduce waste. Another example is to replace single-use with reusable temperature probes that can be designed to meet same infection control standards as their disposable counterparts that will positively affect clinical waste management. Use of combined digital twin with XR for transition from single use to reusable devices will also help address key factors including functionality, cost-effectiveness, infection control protocols, and compliance with regulatory guidelines.

DTs and XR innovation can help inform 3D-models in surgical planning and medical applications [97] including appropriate sterilization modalities bedside 3D-printed devices for use in operating rooms [98], and for personalized medication [99]. Recent XR research has demonstrated that monitoring user eye gaze, heart rate during virtual training can improve one-to-one training and performance [26]. Immersive learning technologies can collect usage statistics such as frequency of training, duration, completion, tasks performed, questions answered and monitor engagement levels (measured in terms of eye tracking, head movement, clicks, and other learner interactions), while the analytics produced confirm that trainees achieve a deep level of understanding of the material. Future TwinXR will inform the dynamic visualization for precision medical device design and use by for healthcare professionals including enhanced product development and prototyping, biocompatibility (3D), human-centric approach for user experience, and multi-actor collaboration and training, and automation.

4. Summary

Healthcare facilities have become reliant on SUD supply chain where there are significant opportunities to introduce more sustainable reuse options for medical devices. However, of parament importance is to meet the pipeline supply of safe, regulated and effective devices for patient needs. Our greater appreciation for design features and the role of cleaning for reusable medical devices will help inform a new generation of effective and sustainable medical devices that includes reducing risk to patients. There is a commensurate need to address bespoke training including advances in material science, microbiological quality and sterility assurance for reuse of medical device. This consideration should also address the testing and introduction of appropriate eco-materials in medical device design and capacity to swop out and introduce sustainable parts for future devices that can be effectively disinfected and sterilized. Support should be given to encourage greater integration of main actors for unlocking sustainable solutions for next generation reusable devices that optimize circularity and waste management, such as using Penta helix hubs that combine academics, healthcare, industry, and regulators with digital solutions. This approach will also harness the subject matter expertise of key enablers including addressing sterility assurance and sustainability from a material science and reuse from a safe medical device waste management perspective.

5. Future Recommendations and the Way Forward

The WHO [4] noted that “several reasons exist for inadequate health care waste services. These include limited legal frameworks (e.g., policies, regulation, guidelines), lack of awareness about the health hazards related to health-care waste, inadequate training in proper waste management, absence of waste management and disposal systems, insufficient financial and human resources and the low priority. Many countries either do not have appropriate regulations, or do not monitor and enforce them”. From review of the published literature, key activities for improving healthcare waste management with focus on medical devices include:

- Adopting a multi-actor approach to investigating supply chain. logistics and appropriate innovation to address medical device waste reuse and scaling from across different healthcare practices globally. that appropriately considers efficacy, financial viability, environmental impact, safety and regulation
- Consensus should be reached on appropriate range of performance measurement indicators to assess environmental impact and underpinning methodologies given that there is frequent variance between published studies influencing robustness and ease of comparison for using different SUDs and RUDs.
- Greater consideration should be given to delineate medical device waste from compositional material (sustainability and functionality) perspective and to apply different high-level disinfection techniques to ensure reuse in a safe manner. There is future scope for using deep learning and automation techniques for

improved efficiencies and scalability; however, these approaches are reliant on the amount and quality of data generated. So effective supply chain, management and scaling is critical.

- Companies engaged in developing innovation to address sustainable medical waste needs must also consider 'green thinking' (including options for CSR) along with applying appropriate LSAs to determine viability of business proposition that also embraces risk mitigation and investment.
- There should be an increased focus on planning for effective medical waste management, such as appropriate location for treatment and reuse that could be accelerated through Penta-helix hubs accommodating stakeholders along with subject-matter experts.
- A decision to invest in sustainable reuse in healthcare that includes budgetary commitment and training would also help stimulate these circulatory.
- Increased awareness and promotion including advocacy where effective sustainable practices that also improve our planetary health area tailored into appropriate strategic policies.
- There are many moving parts to effective medical device waste management; thus, it is important to support and champion early-adopters and to expedite commensurate regulation of these processes.

The WHO [4] noted key elements for the commensurate improvement of healthcare waste management as:

- promoting practices that reduce the volume of wastes generated and ensure proposer waste segregation;
- developing strategies and systems along with strong oversight and regulation to incrementally improve waste segregation, destruction and disposal practices with the ultimate aim of meeting national and international standards;
- where feasible, favouring the safe and environmentally sound treatment of hazardous health care wastes (e.g., by autoclaving, microwaving, steam treatment integrated with internal mixing, and chemical treatment) over medical waste incineration;
- building a comprehensive system, addressing responsibilities, resource allocation, handling and disposal. This is a long-term process, sustained by gradual improvements;
- raising awareness of the risks related to health-care waste, and of safe practices; and
- selecting safe and environmentally friendly management options, to protect people from hazards when collecting, handling, storing, transporting, treating or disposing of waste.

Government commitment and support is needed for universal, long-term improvement, although immediate action can be taken locally.

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