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REVISITING THE CIRCULAR MANAGEMENT OF HEALTHCARE WASTE: THE 10R CIRCULAR ECONOMY HIERARCHY

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ABSTRACT

This is a position paper to support the application of the Circular Economy (CE) hierarchy to management of healthcare waste (HCW). This hierarchy is based on the 10R typology and includes the strategies Refuse, Reduce, Resell/Reuse, Repair, Reprocess, Refurbish, Remanufacture, Repurpose, Recycle and Recover (energy). Disposal was added as a sink of residues from the CE strategies. The need for circular management of HCW using the 10R hierarchy, its comparison with other hierarchies and its relationship with a typical HCW management system are discussed. In the author's view, the 10R hierarchy proposed in this paper is best suited for circular management of HCW, but indicative risks, knowledge gaps and policy recommendations must be addressed. Implementation of the 10R CE hierarchy can accomplish (1) waste prevention, (2) medical product life extension, (3) reduction of environmental footprint, (4) significant cost savings and (5) alignment with major regulations. End-of-pipe treatment and disposal would be required for the downgraded infectious fraction of HCW.

1. INTRODUCTION

In March 2020, the European Commission published its communication "A new Circular Economy Action Plan (CEAP) for a cleaner and more competitive Europe" (EC, 2020). The CEAP is a key component of the European Green Deal, which is the EU (European Union) roadmap towards climate neutrality by 2050. The EU Green Deal is integral to the Commission's strategy to implement the United Nations (UN) 2030 Agenda and its Sustainable Development Goals (SDGs).

The policy framework of the CEAP focuses on the following thematic areas: (1) production of sustainable products, (2) transformation of industrial processes within 7 key product value chains (e.g., vehicles, packaging, buildings, etc.) to unlock economic value and create important synergies, (3) ensure less wastes and more value from using them as toxic-free secondary material, (4) making circularity work for people, cities and regions, (5) implement crosscutting actions, such as tying the Circular Economy (CE) to climate neutrality, and (6) lead efforts at global level, e.g., reach a global agreement on plastics.

Healthcare waste (HCW) exerts significant environmental footprint and its management belongs to the third thematic area listed above. However, established technologies (e.g., recycling, incineration, sanitary landfilling) are typically used and circular management is lacking (Fletcher et al., 2021). In a Waste Management Editorial, Voudrias (2018) outlined the procedure for applying the CE model for management of HCW, based on the EU waste hierarchy. The latter, however, focuses on implementation of the less damaging strategies for waste management rather than on maximizing the value of products, materials and resources in the economy (Fletcher et al., 2021). The production of sustainable products is implicitly included in the prevention strategy of the EU waste hierarchy, but more detailed strategies are needed to accomplish it. This can be done by replacing the EU waste hierarchy with the CE hierarchy, as implemented by Voudrias (2023) for management of COVID-19 HCW. Several studies dealt with circular management of HCW, e.g., Debnath et al. (2022), Fan et al. (2021), Felix et al. (2022), Ibn-Mohammed et al. (2021), Kane et al. (2018), Teymourian et al. (2021) and Wuyts et al. (2020). These and many others were cited in the review by Voudrias (2023).

This is a position paper to support the application of the CE hierarchy to management of HCW. The approach is based on the 10R typology and includes the strategies Refuse, Reduce, Resell/Reuse, Repair, Reprocess, Refurbish, Remanufacture, Repurpose, Recycle and Recover (energy), with Disposal as a sink of residues from all previous strategies (Figure 1). Unlike other R-hierarchies (e.g., 3R), the 10R strategies have the following targets: (1) The first four strategies (Refuse, Reduce, Resell/Reuse, Repair) target

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waste prevention. (2) The next four strategies (Reprocess, Refurbish, Remanufacture, Repurpose) target life extension of medical products being at the end of their lifecycle. (3) The last two R strategies (Recycle, Recover (energy)) and the Dispose strategy target reduction of environmental footprint (Figure 1). The definitions of the R-strategies are according to Reike et al. (2018). A short discussion of each R-strategy follows.

2. THE 10R STRATEGIES

2.1 Refuse (R0)

Refuse is defined as buy less, consume less, prevent waste production and refers to products and substances before they become waste. For example, buying and consuming less is accomplished when hospitals optimize and screen disposable custom packs, which are used to reduce clinical errors and cross contamination. Once opened, their contents become HCW, even if they have never been used.

To prevent waste production, hospitals can implement Life Cycle Assessment (LCA) and "environmentally preferable purchasing" of products and services, which produce less hazardous waste (article 3 of Waste Framework Directive – WFD, 2008) and improve the hospital environment for staff and patients. For example, hospitals can: (1) Offer excess supplies to other healthcare institutions before expiration date, or apply the Chemical Waste Exchange approach (Barbosa et al., 2020). (2) Substitute plastic materials, such as the swabs in test kits, with non-plastic equivalents (Abhilash and Inamdar, 2022). (3) Utilize medical products with lower contents of hazardous components, such as plasticizers, stabilizers and dyes in plastic healthcare products, which could be toxic, endocrine disruptors or carcinogens. EU requires that healthcare products containing hazardous additives at >0.1% w/w to be labelled, thus providing information to stakeholders to make a buying decision.

2.2 Reduce (R1)

Reduce is achieved by using smaller amounts of materials in product manufacturing, extending the useful life of the product before it becomes waste and decreasing unnecessary product use. Examples of materials appropriate for reduce without compromising safety are gloves and other personal protection equipment (PPE) and packaging for PPE, vaccines and test kits. Glove overuse has a negative environmental footprint and results in unnecessary cost increase, which could be avoided by implementing the reduce strategy.

2.3 Resell/Reuse (R2)

This is not a waste management operation, but refers to using again a product or component for the same purpose it was originally conceived. Many healthcare products can be designed for reuse after disinfection. These include: scalpels, surgical and isolation gowns, table covers, plastic sharps containers, vaccine vials, N95 respirators, face masks, other PPE and drapes. There are, also, disposable and single-use materials, such as single-use plastic (SUP) products, which were introduced in the healthcare industry for infection control and convenience, but their abuse resulted in excessive cost and HCW generation. To address the problem of plastic pollution in EU, starting in 2021, all SUP products for which there are reasonable alternatives were banned. However, the COVID-19 pandemic delayed and, in some circumstances, reversed the SUP ban, resulting in an overwhelming generation of masks and other PPE waste.

Although several studies on successful reuse of SUPs have been published, the viable alternative would be the development of reusable healthcare products, such as face masks and isolation gowns for healthcare personnel, because of lower overall cost and lower waste generation (review by Voudrias, 2023).

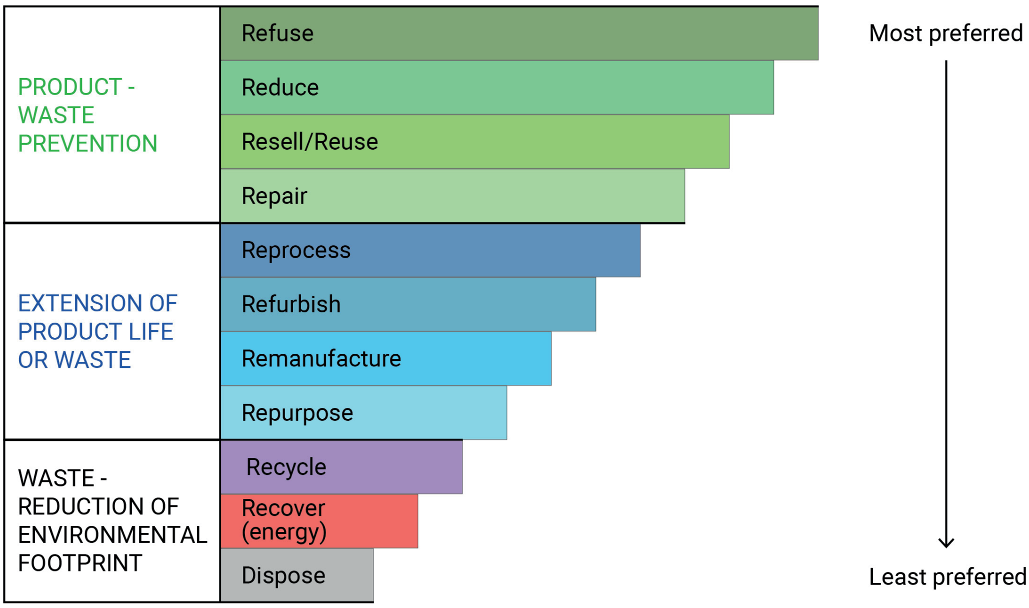

FIGURE 1: Circular economy hierarchy. Further developed based on Reike et al. (2018), Stanislaus (2019) and Voudrias (2023).

2.4 Repair (R3)

Repair is usually applied but not limited to longer-lived medical devices, such as X-ray machines, magnetic resonance imaging and computer tomography scanners, in order to extend their life, make them operate again after a malfunction or to avoid a device failure by applying a maintenance program. If not repaired, these devices would be removed from the economic system and would become HCW. In Europe and North America, repair and maintenance of medical devices is conducted by their manufacturers or specialized third-parties and represent an industry >1 billion USD.

2.5 Reprocess (R4)

Single-use devices (SUDs), such as arthroscopic shaver blades, surgical shavers, surgical staplers, hearing aids, endoscopes, catheters and manual ventilation valves, are suitable disposable devices used by healthcare organizations, instead of cleaning and sterilizing their reusable analogues. All medical devices must be adequately cleaned and sterilized following a single use, in order to prevent potential spreading of pathogens. Thus, reprocessing of SUDs refers to their recovery after repairing, cleaning, sterilizing and repackaging (review by Voudrias, 2023). Reprocessing is performed by device manufacturers or specialized third-parties, with economic savings for hospitals ranging between 40 – 60% of the price of the new device and improved environmental footprint because of diverting SUDs from sanitary landfills and incinerators.

There are two important safety issues caused by: (1) Insufficient sterilization and (2) mechanical or chemical impairment because of repeated SUD reprocessing (Kane et al., 2018). For example, deaths were caused by inadequately sterilized reprocessed endoscopes and catheters. Such problems resulted in loss of trust for reprocessed SUDs, regardless the US Government Accountability Office report stating that “available information does not indicate that use of reprocessed SUDs presents an elevated health risk” (USGAO, 2008). To solve these problems, one strategy could be to design a device for a fixed and predetermined number of reprocessing cycles, before the device becomes obsolete and is disposed of as HCW. Another strategy could be to develop “hybrid” devices with the parts entering the human body to be removable and replaceable. Addressing the safety issues may, also, restore trust for reprocessed devices among healthcare personnel and patients and maintain the economic and environmental benefits (Kane et al., 2018).

2.6 Refurbish (R5) and remanufacture (R6)

Refurbish is defined as replace modules or components in large products at the end or close to the end of their lifetimes, resulting in lower quality (shorter warranty) than the original product (review by Kane et al., 2018). Remanufacture is defined as disassemble, replace modules or components in large products at the end or close to the end of their lifetimes and reassemble, resulting in the same or greater quality than the original product (review by Kane et al., 2018). The most appropriate medical devices for these strategies are those of high value and low criticality, such as imaging equipment, anaesthesia machines, patient monitors, furniture and large surgical equipment, which do not need vigorous sterilization and should be easily accessible for cleaning and part replacement.

2.7 Repurpose (R7)

In repurposing, the original product is used for another function. Repurposing of a medical device means to make it suitable for new healthcare applications, different user cohorts and new geographical areas (Loomba, 2014). It is performed on low criticality and high value devices, such as ultrasound machines, and low criticality and low value medical products, such as face masks, gloves, other PPE. For example, an ultrasound device used in a hospital prenatal care is adapted for clinical applications, such as massage, nerve regeneration or reduction of cancer cells. Waste masks were studied for concrete manufacturing and other civil engineering applications (review by Voudrias, 2023).

2.8 Recycling (R8)

Recycling is defined as using the raw materials of waste components after separation and collection. The recycled materials do not maintain the structure characteristics of the original products and can find many other applications (Reike et al., 2018). There are two types of waste components, which can be recycled: (1) High criticality, low value components, such as syringes, catheters, endoscopes and bandages, which usually become infectious waste and must be disinfected before recycling. (2) Low criticality, low value components, such as blue wrap, IV bottles, other sterile liquid containers, glass vials, Al caps, vaccine plastic packaging, face masks and single-use compression sleeves, after separation from high criticality waste and actually becoming domestic-type waste (review by Voudrias, 2023).

There are, also, recycling barriers, which include: (1) Low cost of virgin raw materials, (2) cost increase because of disinfection for safety reasons, (3) complicated structure of recyclables, (4) legal measures forbidding recycling of hazardous components and (5) “safety-first” culture by erroneously perceiving the recyclable materials as hazardous (review by Voudrias, 2023). In terms of circular economy, the objective is to “upcycle”, i.e., convert the recovered materials into value-added engineering materials from environmental and economic point of view. For example, upcycling of face mask waste can be accomplished by: (1) carbonization to adsorbents, gas sensors, electrodes, carbon nanotubes or (2) catalytic conversion to biofuels (review by Voudrias, 2023).

2.9 Recovery of energy (R9)

HCW contains material with high calorific value, such as plastics, wood, paper and paperboard. The energy embodied in residual HCW can be captured by well-established technologies, such as: (1) incineration of HCW, (2) coprocessing of disinfected HCW components with municipal waste to produce sanitized refuse-derived fuel and (3) pyrolysis to produce syngas, oil and char (review by Voudrias, 2023).

2.10 Disposal

As explained above, the CE approach is possible to specific HCW components, with the remainder to be diverted to incineration or sanitary landfilling after disinfection. The 10R strategies described above, except "refuse" and "reduce", generate residues and waste, which require safe disposal. Similarly, the hazardous compounds of the original material tend to accumulate with recycling and potentially become a threat to human health and the environment, unless safely disposed of (review by Voudrias, 2023).

3. DISCUSSION

3.1 Why circular management of HCW?

Unlike the linear economy model, the objective of the circular HCW management is to extract the maximum value from raw materials and medical products and convert waste to resources. This will result in reduced environmental footprint, e.g., reduced waste production and greenhouse gas emissions, reduced energy consumption and cost savings, as well as in safety improvement for both patients and employees. As an example, it was estimated that a 1000-bed hospital in the USA could reduce waste by 15.5 tonnes/y if it switched to reusable sharp containers from disposable ones, with parallel cost savings of $175,000/y (Kwakye et al., 2011). According to David Lawrence, MD, former Chairman & CEO of Kaiser Permanente, "we think of environmental protection as preventive medicine on a grand scale". Nevertheless, the highest priority of a healthcare institution is to provide high quality care.

Procedures for circular management of HCW using the EU waste hierarchy and COVID-19 HCW using the 10R CE hierarchy were presented by Voudrias (2018) and Voudrias (2023), respectively.

3.2 Relationship between HCW management system and 10R hierarchy

The purpose of the HCW management system is to avoid and/or minimize waste generation and reduce its hazard properties and environmental impact, at the most cost-effective way. An indicative HCW management system consists of the following five component systems: (1) The system of HCW production, (2) the system of handling, segregation, on-site transport and temporary storage at the source, (3) the system of collection and transport out of the healthcare unit, (4) the system of treatment and (5) the system of disposal (WHO, 2014; Voudrias and Graikos, 2014).

The effectiveness of HCW management system can be assessed by waste audits, which can be used to monitor the amounts and types of HCW generation, segregation, storage, transportation, treatment and disposal. This waste composition information can be used to identify and correct wrong management practices (Voudrias, 2018). In the process of waste audit, various monitoring indicators can be used, such as: (1) Total HCW generated in kg or kg/d, (2) HCW unit production rates in kg/patient/d and kg/bed/d, (3) percentages of segregated components, e.g., % infectious or % pharmaceutical waste and (4) percentage of actually collected vs. generated waste (Kermenidou et al., 2019).

There is a two-way relationship between the HCW management system and the 10R strategies. For example, the first four strategies (Refuse, Reduce, Resell/Reuse, Repair) affect mainly the system of HCW production and implicitly all other systems of HCW management, because these are sized and costed based on the amount produced and being treated. The Recover energy strategy will affect the size and cost of treatment and disposal systems.

The system of handling, segregation, on-site transport and temporary storage at the source will involve segregation of HCW in subcategories, according to local or national regulations, for example, infectious, pharmaceutical, sharp, etc. This is a very important separation, because each of the produced subcategories will be subject to management using the appropriate R strategies. In this case, the remaining six strategies (Reprocess, Refurbish, Remanufacture, Repurpose, Recycle, Recover energy) can be used. Implementation of these strategies will obviously affect the design of collection and transport system. If source-segregation is not practiced, the total amount of HCW is considered hazardous and has to be incinerated and landfilled, thus, failing to apply circular management and implementing end-of-pipe treatment.

3.3 The need for the 10R CE hierarchy

For all practical purposes and, in this case, the management of HCW, it is important to develop a common understanding of what CE is. Although the 3R concept of "reduce, reuse, recycle" establishes a generally accepted perception of CE in theory and practice, there are circular systems with varying numbers of R strategies, such as 4R, 5R, 6R and 10R. However, there are different definitions for these strategies in the literature, indicating conflicting views among authors. Not only scientists, but also governments and international organizations use conflicting or divergent definitions. For example, EU uses 3R for "reuse, recycle, recover", whereas the UN and OECD (Organization for Economic Cooperation and Development) use 3R for "reduce, reuse, recycle" (Reike et al., 2018).

In order to provide clarity in the field, Reike et al. (2018) summarized the divergent concepts and synthesized the most common prospects on R-strategies into a single 10R systemic typology. The 10R CE hierarchy of Figure 1 is not identical with the latter, but it is based on a similar typology and defines distinct strategies significantly contributing to CE. Such strategies may need to be combined in practice, depending on the complexity of products or wastes (e.g., HCW) to be managed.

The proposed in this paper 10R categorization system may be used by public authorities, businesses, investors and financing organizations to improve their understanding of activities advancing CE and support them in selecting, financing and developing such activities, with respect to circular management of HCW. By applying the 10R hierarchy, we can achieve increasing resource efficiency and decreasing environmental footprint from HCW management.

3.4 Comparison of different CE hierarchies

The 10R CE hierarchy presented in this paper is based on the 10R typology published by Reike et al. (2018), but it is not identical. The former includes the strategies Reprocess and Dispose and lacks the strategy Remine of the latter. The Reprocess strategy is applied to SUDs, an important category of HCW, and, in the author's view, should be a distinct strategy in the 10R hierarchy for management of HCW. The Dispose strategy is necessary for management of residues generated by higher priority R-strategies. Cossu and Williams (2024) emphasized the crucial need of acceptable "Back to Earth" sinks during the global transition to a circular economy. The Remine strategy proposed by Reike et al. (2018) refers to recovering resources from old landfills, but in the case of HCW disposal, such recovery is probably not significant. Therefore, Remine is implicitly included in the Dispose strategy.

The comparison of different CE hierarchies with respect to their R-strategies is presented in Table 1. The Fan et al. (2021) hierarchy is identical to that of Reike et al. (2018), whereas the Stanislaus (2019) hierarchy is a 9R hierarchy, almost identical to that of Reike et al. (2018), but lacking the Remine strategy. In the author's opinion, the 10R hierarchy proposed in this paper is better suited than other R-hierarchies (e.g., 3R) for circular management of HCW for the following reasons:

1. It emphasizes on waste prevention, before materials become HCW (e.g., Refuse, Reduce, Reuse).
2. It emphasizes on product life extension, going beyond Reuse (e.g., Repair, Reprocess, Refurbish, Remanufacture, Repurpose). For comparison, the 3R hierarchy after Reuse would go directly to Recycle.
3. It reduces environmental impact, using the energy-intensive strategy of Recycling as the last resort. By minimizing the amount of HCW going to Recover (energy) and Dispose (sanitary landfilling), it lowers the environmental footprint of hospitals and other healthcare institutions. By comparison, in the 3R hierarchy Recycling is a major strategy, accepting significantly larger amounts of materials.
4. It provides significant cost savings through Repair, Reprocess, Refurbish, Remanufacture and Repurpose of medical devices, instead of purchasing new ones. It, also, creates new employment positions for these industries. For comparison, the 3R approach would be to Recycle after a single use or reuse.
5. It aligns with policy frameworks, such as the CEAP of the EU and WHO guidelines on HCW management.

4. FINAL REMARKS

The CEAP of EU does not specifically address HCW, but its emphasis on CE and sustainable waste management provides the legal basis that can be adopted by HC institutions to enhance circular practices and sustainability. However, adopting the CE strategy to HCW management may be subject to risks, such as: (1) Low market penetration of reprocessed SUDs, because of negative public perception, (2) presence of hazardous substances in CE products and (3) lack of economic incentives, such as tax reductions for CE products. There are knowledge gaps, which need to be addressed, for example: (1) Manufacture healthcare plastic products using one type of plastics with minimum pigment content, (2) develop technologies for separation and recycling of complex plastic healthcare products and (3) manufacture "hybrid" devices with the parts entering the human body to be replaceable. New policy initiatives are, also, necessary, for example: (1) Regulate and tax medical products with no recycling potential, (2) implement "environmentally preferable purchasing" and (3) educate and train the public in CE-related issues. In the author's view, the 10R hierarchy proposed in this paper is best suited for circular management of HCW, but the above indicative risks, knowledge gaps and policy recommendations must be addressed.

As indicated above, there are many HCW individual components, which could be managed by selecting R-strategies from the CE hierarchy and avoiding incineration and sanitary landfilling. For example, plastic materials are some of the most abundant components of HCW and persistent environmental contaminants at the global scale. Personal protective equipment (gloves, masks,

TABLE 1: Comparison of different CE hierarchies for management of HCW, with respect to their R-strategies.

This paper	Reike et al. (2018)	Fan et al. (2021)	Stanislaus (2019)
Refuse	Refuse	Refrain (Refuse)	Refuse
Reduce	Reduce	Redesign and Reduce	Reduce
Resell/Reuse	Resell/Reuse	Reuse	Reuse
Repair	Repair	Repair	Repair
Reprocess	-	-	-
Refurbish	Refurbish	Refurbish	Refurbish
Remanufacture	Remanufacture	Remanufacture	Remanufacture
Repurpose	Repurpose	Repurpose	Repurpose
Recycle	Recycle	Recycle	Recycle
Recover (energy)	Recover (energy)	Recover	Recover
Dispose	Remine	Remine	-

gowns) are plastic materials, which were accumulated in residential districts, floating in coastal waters and washed up on shores around the world during the COVID-19 pandemic. By applying circular management activities, the global persistence problem of plastics can be minimized or solved.

The purpose of the HCW management system is to avoid and/or reduce waste generation and reduce its hazard properties and environmental impact, at the most cost-effective way. Implementation of the 10R hierarchy can accomplish (1) waste prevention, (2) medical product life extension, (3) reduction of environmental footprint, (4) significant cost savings and (5) alignment with major regulations. Focusing directly on recycling does not necessarily promote CE, because recycling dismantles products to recover and use them as raw materials, instead of maintaining them in the economy. Therefore, priority should be given to other R-strategies, according to Figure 1. Furthermore, creating value from the dominant infectious fraction (containing usually unsorted contaminated with bodily fluids and downgraded materials) requires excessive amounts of energy and increased cost. To close material cycles of such materials, treatment and disposal at their end-of-life cycles would be necessary.

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