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## Review

# A framework for assessing the circularity and technological maturity of plastic waste management strategies in hospitals

C.A. Fletcher <sup>a</sup>, R. St. Clair <sup>b</sup>, M. Sharmina <sup>b,\*</sup><sup>a</sup> Department of Natural Sciences, Manchester Metropolitan University, Manchester, United Kingdom<sup>b</sup> Tyndall Centre for Climate Change Research, School of Engineering, University of Manchester, Manchester, United Kingdom

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## ABSTRACT

Consumer single-use plastic waste has received much attention from the public, policy-makers and researchers. However, the management of such waste in medical settings has been less well examined. This article reviews existing evidence on waste management strategies within hospitals, with a particular focus on single-use plastics. The article develops the 'Waste Hierarchy-Technology Readiness Levels' framework and assesses each waste management strategy against it, indicating the maturity of the technology and the strategy's position in the Waste Hierarchy, in addition to its relative adherence to circular economy principles. Findings show that currently dominant waste management strategies include disposal to landfill, incineration and recycling, while alternative strategies include reduction, reuse, bioremediation and chemical recycling. Most strategies reviewed are at a high level of technology readiness and at a low level on the Waste Hierarchy, demonstrating that hospital waste management strategies tend to be based on mature technologies and suggesting a need for more innovative, circular economy solutions. Exceptions, which are at a high level on the Waste Hierarchy but at an early stage of development, include bioremediation using microbial action and chemical recycling using hydrophilic solvents. This review highlights a disparity between the levels of alignment with the circular economy principles in waste management strategies of developed and developing nations, suggesting a need for both international collaboration and strategies sensitive to specific regional contexts.

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\* Corresponding author. Tyndall Centre for Climate Change Research, H Floor, Pariser Building, Sackville Street, University of Manchester, Manchester, M13 9PL, United Kingdom.

E-mail address: [maria.sharmina@manchester.ac.uk](mailto:maria.sharmina@manchester.ac.uk) (M. Sharmina).

## 1. Introduction

Plastic products are ubiquitous and often indispensable throughout people's everyday lives, but the production and disposal of plastics can damage the environment. In particular, discarded plastics can accumulate in the environment unless destroyed through thermal treatment (Geyer et al., 2017). The production and incineration of plastics releases approximately 400 Mt of carbon dioxide every year (European Commission, 2018), while plastic waste contaminates freshwater systems (Wagner et al., 2014), the soil (Rillig, 2012), and the oceans, damaging marine ecosystems (Barnes et al., 2009). It is estimated that without improvements in waste management, by 2050, approximately 12,000 million tonnes of plastic waste will have accumulated in landfill sites or the natural environment (Geyer et al., 2017). Following the dramatic increase in medical plastic waste arising from the COVID-19 pandemic (Prata et al., 2020), the need to manage such waste in innovative and joined-up ways has become even more urgent (Patrício Silva et al., 2020). In order to mitigate the environmental impacts of plastic waste, it is therefore necessary to investigate alternative design, production and disposal processes while considering how to manufacture durable products that last longer and are easier to repair, reuse and recycle.

The management of plastic waste is a notoriously difficult area, with multiple methods for separation and recovery and no consensus on an optimal strategy (Rigamonti et al., 2014). Furthermore, while waste management is a global issue, different countries are at varying stages of progress in the development and adoption of sustainable practices, with cities and regions implementing strategies to suit their particular needs (ElSaid and Aghezzaf, 2018). The European Union (EU) is seen as a world leader in its approach, as its introduction of the Waste Hierarchy through the Waste Framework Directive (Directive 2008/98/EC) resulted in landfill diversion and improvements in waste management across member states. The 2015 European Circular Economy Package subsequently reiterated the Waste Hierarchy, emphasising reuse, recycling and continued diversion from landfill (Marin et al., 2018).

The Waste Hierarchy describes the relative environmental harm of a variety of waste management methods in order to promote the implementation of less damaging strategies. It consists of five levels, starting with prevention as the highest priority at the top of the pyramid, followed in reducing preference by preparation for reuse, recycling and recovery. Disposal is positioned at the lowest level of the pyramid to be considered only as a last resort (DEFRA, 2011). In a circular economy, waste and pollution are designed out of systems, while products and materials are kept in use for as long as possible through sharing, reusing, repairing and recycling, and natural systems are given space to recover and regenerate (European Parliament, 2016). According to the circular economy principles, the higher up the Waste Hierarchy a process, the higher the level of circularity it promotes (DEFRA, 2011).

The European Commission's Circular Economy Action Plan recognises plastics as a key priority (European Commission, 2020), and the European Strategy for Plastics in a Circular Economy identifies consumers as "key players" who should be "aware of the need to avoid waste, and make choices accordingly" (European Commission, 2018). While popular attention has been focused on plastic packaging for consumables visible to the public eye (Burgess et al., 2021), there are other areas of everyday life where less light has been shed and where individual buying power has limited control (Gibbens, 2019).

This paper contributes to the understanding of one such issue by focusing on plastic waste management in hospitals, an area largely distant from public discourse and lacking academic attention, particularly in relation to the principles of circular economy (Rizan et al., 2020). Academic reviews of evidence in this area have so far focused on infectious medical waste (Windfeld and Brooks, 2015), specific countries such as Australia (e.g. Wyssusek et al., 2019), specific parts of hospitals such as operating rooms (e.g. Beloeil and Albaladejo, 2020), or specific products such as personal protective equipment (e.g. Rowan and Laffey, 2021). This review adds to this body of literature by comparing how plastic waste is managed in both developed and developing countries, through the lens of a theoretical framework combining the circular economy principles and technological readiness levels of waste management strategies.

Plastic products such as surgical wraps, drapes, gowns and blister packs, are widely used in the medical industry due to their ready availability, low cost and sterile properties (Chauhan et al., 2019). Hospitals use various types of plastic. One example, Polyvinyl Chloride (PVC), is commonly found in medical equipment such as oxygen masks, post-operative facemasks and fluid administration kits and tubes. The prevalence of PVC is particularly problematic, given that it is often disposed of through incineration, a process that generates harmful chlorine gases. While the recyclability of PVC presents an opportunity for near-term improvements to collect and recycle used hospital equipment (Chief Medical Officer, 2017), more advanced waste classification and separation techniques would be required to avoid contamination of waste streams (Hopewell et al., 2009). Alternatively, PVC might need to be phased out altogether and replaced by plastics more amenable to the circular economy principles.

Waste management strategies in hospitals are diverse and regulations differ between regions. For instance in the United Kingdom (UK), trusts within the National Health Service (NHS) are legally required to take the Waste Hierarchy into consideration in order to transition towards recovery, recycling, reuse and reduction (Chief Medical Officer, 2017), whereas in Libya, city hospitals often have no guidelines in place for waste separation, classification or disposal (Sawalem et al., 2009). In some developing nations, such as Pakistan (Ali and Geng, 2018) and India (Chauhan, 2020), innovative waste management strategies are unaffordable, and uncontrolled dumping of waste in unregulated landfill is still standard practice for hospital waste disposal (Singh and Singh, 2014).

In line with Rizan et al. (2020)'s recent call for a re-evaluation of plastics in healthcare, this paper provides a synthesis of literature on waste management practices within hospital settings across the globe. The focus here is on single-use plastics and their waste management through the combined lenses of circular economy and technological maturity. Specifically, this paper advances understanding in this important area by answering the following research questions: (RQ1) what plastic wastes are generated within a hospital setting; (RQ2) what current waste management strategies are employed to deal with the plastic wastes generated; and (RQ3) what alternative waste management strategies have been explored. Using the Waste Hierarchy-Technology Readiness Levels (WH-TRL) theoretical framework, existing and alternative waste management strategies are assessed on the basis of their position on the Waste Hierarchy, their readiness for implementation, and by extension, their contribution to a circular economy. The methodology is described in the next section, followed by results of the literature search and synthesis, where data is mapped against the WH-TRL framework. The paper concludes with a discussion of key

findings and suggestions for further advancing this area of research.

## 2. Methods

A systematic review of secondary sources, i.e. peer-reviewed journal articles, identified existing and novel strategies for the management of waste plastics generated by hospitals. For the purpose of this study, a framework combining the Waste Hierarchy with Technological Readiness Levels (WH-TRL framework) was developed to assess all waste management strategies identified within the secondary sources.

### 2.1. Identifying literature

Literature searches were completed in the following databases: Scopus, Science Direct and Web of Knowledge, in August 2019 and, as an update, in October 2020. To achieve the aims of this study, this paper first identified articles concerned with the generation and management of plastic waste within a hospital environment. Here, database searches were targeted at an article's title, abstract and keywords, with the following Boolean search string: (plastic waste) AND (hospital OR medical OR clinic) AND (waste management). A breakdown of the number of hits for each database using this search string is shown in Table 1. In total, 339 articles were found and imported citations into the reference management software, EndNote X9 (Clarivate Analytics). Full texts (182 articles) were then downloaded, both through open access and institutional access, excluding the references that did not have a full text available.

Any duplicate citations were then removed, for example the same article identified by a different database, or a report later published as a peer-reviewed journal article. The remaining 137 articles were assessed against the inclusion and exclusion criteria shown in Table 2 over two selection stages. The first selection stage applied the criteria to the titles and abstracts only and retained 60 articles. The second selection stage applied the criteria to the whole paper, where a final reference list of 41 articles was produced. Only studies published within the last 15 years (2005–2020) were retained. This timeframe reflects a specific period of evolution within EU waste legislation, which covers the amendment of the Waste Framework Directive in 2006 and 2008, as well as the publication of the Circular Economy Package in 2015. In total, 36 articles were taken forward for review, with 9 of them identified during the second search in October 2020.

### 2.2. Data extraction and mapping

The content of the selected documents was mapped using Excel 2016 (Microsoft), where bibliographic and contextual information (full quotes with page numbers) were first extracted. The bibliographic information included the name(s) of author(s), date of publication, the article's title and the name of the journal or source where the article was published. Contextual information included the geographic region plus any reference to local laws, legislation or regulation made in the document.

To identify the types of plastics and plastic products that are used and discarded in hospitals, information pertaining to the

generation of plastics wastes was extracted as full quotes with page numbers. This information included general references to using and discarding plastic products, the type of polymers (e.g. PVC) being used and discarded, and the original use(s) for the plastic products.

To identify waste practices, information was extracted on both current and alternative waste management strategies for the collection and management of plastic wastes, again as full quotes with page numbers.

### 2.3. Data analysis, and development of the assessment framework

Extracted information was analysed to present an overview of the studies included, to determine what, and how many, plastic products are used and disposed of within a hospital setting, and to highlight differences in waste policy by nation. Using the UN World Economic Situation and Prospects 2019 report (UN, 2019), each article was categorised, based on the nation of study, as either developed or developing. These categories are reflective of basic economic conditions.

To contribute to the circular economy, waste management strategies should be positioned toward the top of the Waste Hierarchy, while to achieve this in line with the EU 2030 plastic recycling target, strategies should be ready for implementation. To assess both the implementation readiness and a strategy's place in the Waste Hierarchy, the current and alternative waste management strategies were evaluated against the WH-TRL framework adapted from Rybicka et al. (2016).

The WH-TRL framework (see Fig. 1) assesses strategies based on their position on the Waste Hierarchy and the maturity of the technology involved. Here, the Waste Hierarchy has been expanded from the five-level hierarchy used within EU waste policy to the ten-level hierarchy suggested by Fletcher and Dunk (2018). The ten-level hierarchy is a more comprehensive tool that highlights the differences in value retention throughout material recycling methods. Recycling methods that preserve or increase the inherent value of a material within a closed-loop system are referred to as re-cycling and up-cycling respectively, whereas methods resulting in the degradation of value, such as those within open-loop or cascading systems, are known as down-cycling (Reike et al., 2018). In light of the circular economy principles, where the aim is to retain the value of materials over successive lifecycles, up-cycling and re-cycling are preferred recycling methods. The WH-TRL framework also separates disposal to landfill into two parts to show the distinction between the use of unregulated open dumps and a sanitary controlled landfill.

To determine if a strategy is ready for implementation, Technology Readiness Levels (TRLs) were used (Sausser et al., 2006). TRLs indicate the maturity of a technology and can be used as benchmarking tools to track progress and support development (Ji et al., 2016). Generally, there are nine TRLs, which can be grouped into six activities: basic technology research (TRL 1–2), feasibility studies (TRL 2–4), technology development (TRL 3–6), technology demonstration (TRL 5–7), development and demonstration of systems and subsystems (TRL 6–9) and system test, launch and operations (TRL 8–9) (TEC-SHS, 2008). Information extracted from each study was used to infer a TRL for the current and alternative waste management strategies discussed.

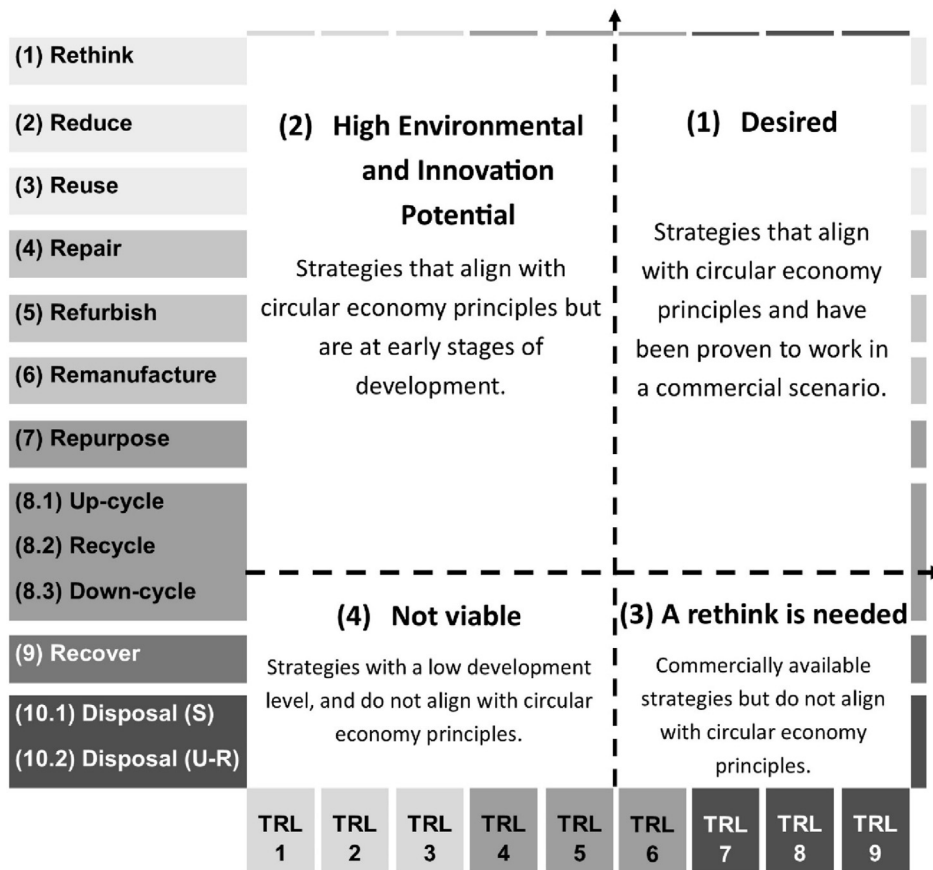
By assessing waste management strategies in terms of position on the Waste Hierarchy and level of technology readiness, alignment to the circular economy can be determined. Furthermore, by using both concepts, strategies can be prioritised for development and implementation, where strategies located within quadrants (1) and (2) can be classified as desired strategies that can be implemented immediately and desired strategies that require more

**Table 1**  
Number of hits from each database.

Source	Total hits	Total with full texts available
Science direct	26	19
Scopus	172	76
Web of Science	141	87
Total	339	182

**Table 2**  
Inclusion-exclusion criteria for selecting appropriate secondary sources.

Inclusion criteria	Exclusion criteria
Include studies in English. Include peer-reviewed studies published in academic journals.	Exclude studies that are not focused on a hospital waste e.g. those concerning dentistry waste, vet waste.
Include studies that identify plastics wastes (original use, type of plastic and amounts) generated in a hospital, clinical or medical setting. Include studies that explore current waste management strategies for hospital waste.	Exclude studies that do not focus on material wastes e.g. those concerns with wastewater or waste energy and heat. Exclude studies that focus solely on catering or non-medical wastes that are generated in a hospital.
Include studies that explore alternative waste management strategies for hospital plastic wastes – this can be at laboratory (proof of concept and feasibility), development (prototype and demonstration) or operational (implementation and roll out) phases.	Exclude studies that solely focus on clinical, hazardous or toxic wastes without exploring waste management strategies.



**Fig. 1.** Waste Hierarchy-TRL framework (adapted from Rybicka et al., 2016). A distinction is made between sanitary landfill (S) and unregulated rubbish dumps (U–R). The horizontal dotted line shows the border between circular economy measures (above the line) and the rest of the Waste Hierarchy (below the line).

research and developmental time before implementation. Strategies located in quadrants (3) and (4) can be conceptualised as existing strategies that need to be replaced and unviable strategies respectively. Fig. 1 reflects the EU 2030 plastic recycling target, with recycling (WH 8) being the minimum action a strategy should aim to achieve. To promote greater alignment to the circular economy, strategies should aim for actions with greater circularity (WH 1–7).

### 3. Results

This study reveals an emerging area of research, with a limited amount of literature currently in existence concerning the management of plastic wastes generated by hospitals. However, the number of nations in which the studies were situated, particularly concerning their different economic development levels

(approximately 55% and 45% for studies based in developing and developed nations, respectively), highlights the generation of hospital plastic wastes as an important global issue. The following sections present the results of the review, organised with respect to the research questions posed.

#### 3.1. RQ1: type of plastics and plastic products discarded by hospitals

This review highlights the range of plastic products and plastic types utilised, and then discarded, by hospitals. As shown in Table 3, blue wrap (and similar products) and packaging are the most common plastic products mentioned in the literature reviewed, followed by generic plastic items, then plastic tubing, bottles and syringes. This finding is to some extent consistent with





co-polymers of PE-PP, and 3% Polyurethane (PU) (McGain et al., 2009a). Finally, in another study of operating rooms in Australia, Polyethylene Terephthalate (PET) was 40%, PVC 23%, PP 21%, co-polymers of PE-PP 10%, and PU 6% (Wyssusek et al., 2020).

### 3.2. RQ2: current strategies employed to manage plastic wastes within hospitals

Table 4 gives a breakdown of current waste management strategies within the reviewed articles, presented by economic development level of the nation studied. With one exception (Noori et al., 2020), studies based within developing nations mention sanitary waste management systems (sanitary landfill, sterilisation and incineration) at best, for example in Burundi (Niyongabo et al., 2019b), with uncontrolled landfill still employed by some, for example in India (Singh and Singh, 2014), Pakistan (Ali and Geng, 2018) and Iran (Taghipour and Mosaferi, 2009). Conversely, the studies based within developed nations, such as Australia (Barracough et al., 2019), Canada (de Darren et al., 2016), and Germany (Vogt and Nunes, 2014) often employ waste management strategies higher up the Waste Hierarchy including source segregation and recycling.

While a disparity in waste management systems is clear across the developmental levels, disposal to landfill is the most prominent strategy, mentioned in 85% of studies ( $n = 17$ ) focused on developing nations and in 94% of studies ( $n = 15$ ) focused on developed nations. Incineration is the second most prominent strategy for developing nations, where over half ( $n = 11$ , 55%) of the articles reviewed referred to incineration as a current waste management strategy. In developed nations, both incineration and recycling are equally as prominent, with several articles ( $n = 7$ , 44%) referring to established incineration and/or recycling strategies.

In addition to the final waste management strategies, pre-treatment stages were also present across both developed and developing nations. Sterilisation, for example via autoclave, microwave radiation, chemical disinfection or thermal oxidation, is used prior to incineration and disposal to landfill in developed (e.g. Mosquera et al., 2014) and developing (e.g. Alagha et al., 2018) nations. Source segregation, likely used to enhance recycling, was only referred to in articles from developed nations including the United States (Albert and Rothkopf, 2015) and Australia (Barracough et al., 2019), whereas co-mingled recycling was mentioned in all the articles.

Studies on current waste management strategies should ideally distinguish between reprocessing, mechanical recycling and chemical recycling (Subramanian, 2019). However, with the exception of the three papers specifically focused on chemical recycling, e.g. using fungi (Pradeep et al., 2013) and switchable-hydrophilicity solvents (Yousef et al., 2018), none of the studies goes into detail about the method of recycling currently used. The papers reviewed tend to focus on the collection and separation of the waste and have little concern about what happens once the waste is collected or sent for recycling. Thus, with the exception of hazardous and unhygienic wastes that are generally collected separately and disposed of via incineration, the majority of plastic waste generated within hospital is managed through existing municipal waste collection and management systems.

Stepping back one stage, to consider the processes for sorting and separating recyclates, again very few studies provide any detail. Studies based in the United States (Albert and Rothkopf, 2015) and Lithuania (Yousef et al., 2018), briefly mention material recovery facilities (MRFs). Other terms used include "regulated waste places" (Lee and Mears, 2012), "offsite treatment facilities" (Niyongabo et al., 2019b) and "sorting facilities" (Wyssusek et al., 2019). Lee and Mears (2012) and Weiss et al. (2016), both of

which are studies based in the United States, mention special arrangements with external organisations and charities to recycle blue wrap.

A final point to note, is the apparent disconnect between waste policy development by policy makers and implementation by healthcare practitioners, evident in studies across both developing and developed nations. There are recurring themes within the reviewed literature, mainly concerned with inadequate personnel training. For example, although health centres in Thailand should follow governmental guidelines to control and manage waste, implementation is often weakly regulated and poorly managed, leading to incorrect and ineffective handling of waste by healthcare practitioners and waste workers (Puangmanee and Jeeranai, 2020). Similarly, while healthcare waste is strictly regulated in Australia, appropriate source segregation of wastes is often inadequate, possibly resulting from limited knowledge about waste management, or even complacency, among hospital staff (Wyssusek et al., 2019). Poor source segregation is often caused by misclassifying non-infectious waste as hazardous (Mosquera et al., 2014). Lack of financial resources and time are cited as additional reasons for poor implementation of waste management policies (Sahni et al., 2018). In turn, these problems may lead to more waste requiring specialised treatment and reduced participation in recycling schemes.

### 3.3. RQ3: alternative waste management strategies suggested for the management of plastic wastes within hospitals

Within the articles reviewed, recycling was found to be the most popular alternative waste management strategy (55%,  $n = 20$ ), followed by schemes to reduce the amount of plastic waste generated and to reuse the plastic products (both 31%,  $n = 11$ ), and incineration (19%,  $n = 7$ ). For example, increased recycling could divert 38% of waste within a US emergency department away from landfill (Hsu et al., 2020), while Stall et al. (2013) estimates a 53% reduction in the volume of surgical waste when reusable products replace disposable ones.

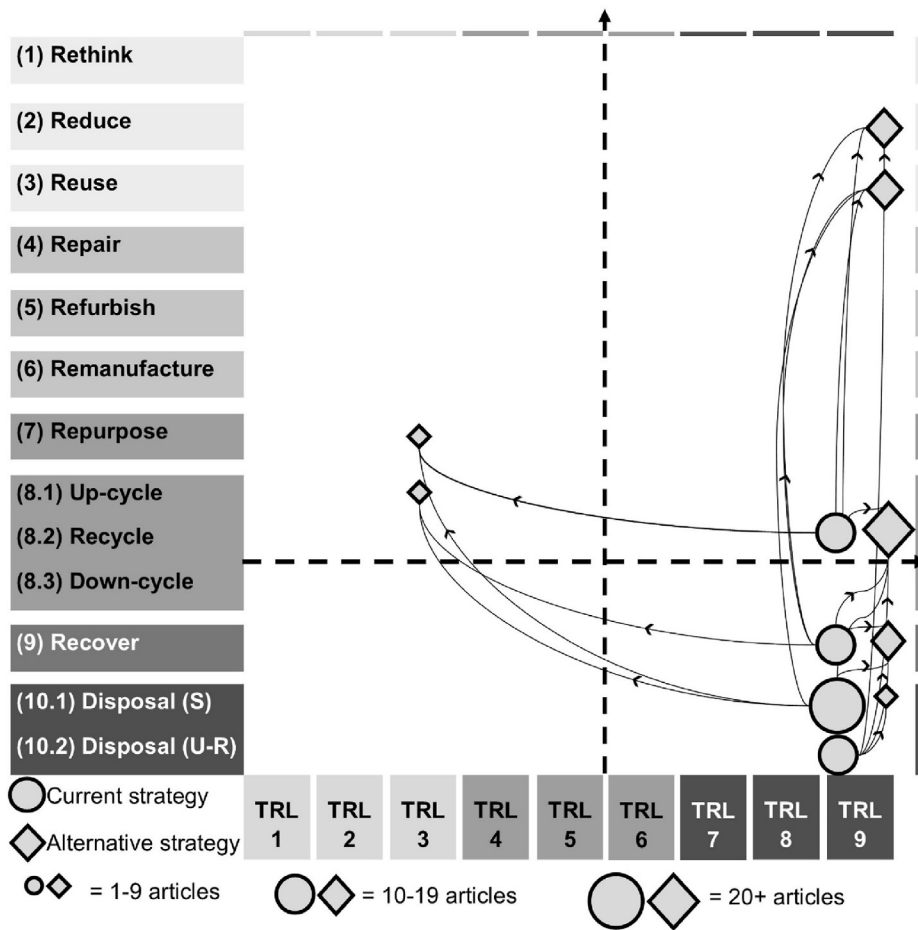
The finding about reuse as a proposed alternative strategy is particularly curious, given stringent hygiene requirements in hospital settings. The switch to single-use plastic products across clinical setting in the 1980s was to counteract concerns about blood-borne diseases (Wyssusek et al., 2019). Despite these concerns and the fact that reuse does not always show environmental benefits on a life-cycle basis (Rizan et al., 2020), some of the reviewed studies advocate for reusable alternatives, such as reusable sharps containers (McPherson et al., 2019) and reusable linens (Stall et al., 2013). For example, surgical coverage (items that are opened before surgery but not used) could be reduced by 45% per surgery, if single use plastic products were replaced with reusable alternatives, in combination with educational programmes and redesigned supply lists (Stall et al., 2013). Where opened but unused products are uncontaminated, they could be donated to developing countries, to medical or veterinary schools for training, or to schools as art supplies (Wyssusek et al., 2019). Certainly, all products should be decontaminated through e.g. autoclaving or chemical sterilisation before each use (Thiel et al., 2017).

Within the Waste Hierarchy, both incineration and pyrolysis are categorised as the 'recover' strategies (see Fig. 2). In the reviewed literature, four studies suggest incineration (e.g. Alagha et al., 2018) and four studies suggest pyrolysis (Qi et al., 2018) for alternative waste management. Incineration only recovers energy, whereas pyrolysis produces three products: a high calorific gas, combustible oil and a solid residue. However, the value of the pyrolysis products, either as a fuel in energy generation or as a feedstock in material production, depends on the composition and quality of plastics in the waste stream (Paraschiv et al., 2015).

**Table 4**  
Current waste management strategies as mentioned by the reviewed articles, presented by economic development status of nations studied within the articles (sorted by publication year). Note that no papers mention pyrolysis as a current strategy.

References		Developed nations						Developing nations							
		Recycling	Pyrolysis	Incineration	Sanitary Landfill	Uncontrolled	w. source segregation	w. sterilisation	Recycling	Pyrolysis	Incineration	Sanitary Landfill	Uncontrolled	w. source segregation	w. sterilisation
Aragaw,	2020														
Hsu et al.,	2020														
Lourenço et al.,	2020														
Noori et al.,	2020														
Puangmanee and Jearanai	2020														
Ahmad et al.,	2019														
Barraclough et al.,	2019														
McPherson et al.,	2019														
Niyongabo et al., (a)	2019														
Niyongabo et al., (b)	2019														
Puangmanee and Jearanai	2019														
Wyssusek et al.,	2019														
Alagha et al.,	2018														
Ali and Geng,	2018														
Kalogiannidou et al.,	2018														
Qi et al.,	2018														
Sahni et al.,	2018														
Yousef et al.,	2018														
Shinn et al.,	2017														
Thiel et al.,	2017														
de Darren et al.,	2016														
Weiss et al.,	2016														
Albert and Rothkopf,	2015														
Paraschiv et al.,	2015														
Piccoli et al.,	2015														
Mosquera et al.,	2014														
Singh and Singh,	2014														
Vogt and Nunes,	2014														
Pradeep et al.,	2013														
Stall et al.,	2013														
Lee and Mears,	2012														
Pradeep and Benjamin,	2012														
McGain et al.,	2009														
Sawalem et al.,	2009														
Taghipour and Mosaferu,	2009														
Sabour et al.,	2007														





**Fig. 2.** Transition from current to alternative waste management strategy when mapped using the WH-TRL framework. The horizontal dotted line shows the border between circular economy measures (above the line) and the rest of the Waste Hierarchy (below the line). The sizes of the circles and diamonds reflect how many articles in the literature sample mention particular waste management strategies. Acronyms: S – sanitary landfill; U-R – unregulated rubbish dumps. TRL – technology readiness level.

Disposal to landfill, specifically with the use of sanitary or engineered landfill sites, was proposed by four studies as an alternative waste management strategy. All four of these studies were based in developing nations: Burundi (Niyongabo et al., 2019a), Thailand (Puangmanee and Jearanai, 2020) and Libya (Sawalem et al., 2009), where disposal to an uncontrolled landfill is the current norm.

Using the WH-TRL framework, the current and alternative waste management strategies for each article reviewed were mapped (see Fig. 2). The framework plots existing strategies from the literature in circles and alternative strategies in diamonds, while the sizes of the circles and diamonds within the figure demonstrate the number of articles focusing on these particular strategies. Arrows highlight the direction for improvement between strategies discussed in the reviewed studies. Depending on the individual paper, the alternative strategy would have been either physically implemented or theoretically suggested.

Within the articles reviewed, the vast majority of alternative waste management strategies are higher up the Waste Hierarchy when compared with the current strategies employed. This is even true where disposal is introduced as an alternative strategy, due to the current strategy being the use of unregulated dumps (Level 10.2), and the alternative strategy being the use of sanitary landfill (Level 10.1). The only exceptions to these improvements are alternative strategies introduced at the same Waste Hierarchy level as the current strategy they are replacing. Such alternatives include

incremental changes that improve efficacy or efficiency but do not move the strategy further up the Waste Hierarchy, such as segregation and sterilisation of waste (Kalogiannidou et al., 2018) or the development of improved incineration standards (Ahmad et al., 2019).

The majority (83%) of the alternative strategies suggested would positively contribute to the 2030 plastic recycling targets set by the EU on which the WH-TRL framework threshold draws. To achieve these recycling targets, strategies need to be implementable. In this review, the vast majority of the alternative strategies achieve a TRL level of 9. This indicates that these strategies have been successfully implemented and replicated within waste management systems around the world. The majority of the alternative strategies seek to introduce source-segregation to initiate and/or improve traditional recycling schemes. Traditional recycling, which has been widely adopted, is limited to mechanical recycling where polymers are shredded, melted and remoulded (Garcia and Robertson, 2017); however, the methods used and the relative ease of recycling differs between polymer type. For example, thermoplastics such as PET, PE and PP all have a high potential to be mechanically recycled, where the value of the material is maintained, whereas thermosetting plastics such as Polyester, cannot be mechanically recycled and thus tend to be down-cycled for use as a filler (Hopewell et al., 2009). Perhaps most concerning, is the impact of mixed plastic types within a waste stream. For example, Hopewell et al. (2009) note the bi-directional effect of mixing PVC and PET, where the value of the

recycled PET is degraded by the presence of PVC due to inherent immiscibility and differing melting temperatures, and vice versa. Of course, the issues surrounding the impact of mixed waste streams on the recyclability of plastics are not confined to those discarded from a medical setting.

Of the articles reviewed, only four introduce alternative strategies that are immature, achieving a TRL level of 3, indicating that they are at the proof of concept stage. Three of these studies consider chemical recycling through bioremediation by microbial action (Pradeep and Benjamin, 2012) and chemical recycling using hydrophilic solvents (Yousef et al., 2018). The final study, Noori et al. (2020), considers the repurposing of waste medicine wrappers for use as a low-cost electrode material within a microbial fuel cell to generate electrical energy. Since these strategies are located within quadrant (2) of the WH-TRL framework, they demonstrate the potential for further development in order to achieve commercially viability and subsequent implementation. Furthermore, as these are mapped at a higher Waste Hierarchy level (Levels 7 and 8.1) than traditional recycling strategies (Level 8.2) they are more closely aligned with the circular economy principles.

#### 4. Discussion

The findings in this review highlight an apparent discrepancy between the plastic material most frequently mentioned in the literature sample (PVC) and the most frequently mentioned plastic products (blue wrap, drapes and gowns, and packaging), which are normally made of Polypropylene, Polyester and Polyethylene (Song et al., 2011). However, this discrepancy reflects that research tends to focus on, firstly, the high volumes of discarded blue wrap, drapes and gowns (Montazeret al., 2010), and, secondly, the challenges associated with managing PVC-containing waste streams. PVC is particularly difficult to manage as it contaminates other plastic wastes (Hopewell et al., 2009), and even PVC-only waste streams consisting of different types of PVC tend to degrade the recycle quality.

In the reviewed literature, all of the waste management strategies currently used in hospitals draw on mature technologies (see Fig. 2). Understandably, hospitals are conservative environments that err on the side of caution and safety when it comes to rolling out innovations (Chauhan et al., 2019). Compounding the apparent lack of innovations currently employed within hospitals is the scarcity of novel technologies proposed for future waste management strategies. While several of the reviewed papers did suggest 'alternative' strategies such as source segregation (e.g. Albert and Rothkopf, 2015), the vast majority of the alternatives were based on mature technologies (e.g. Van Dooren, 1991). In other words, there was clear tension between the term 'alternative' and the high TRL of those strategies, showing that they are not necessarily 'innovative'. This reliance on existing technologies and waste management strategies may have long-term repercussions, as it risks locking hospitals into wasteful infrastructures and practices for many years.

Nonetheless, the dominance of tried-and-tested source segregation as an 'alternative' waste management strategy in hospitals is a positive development. Given the prevalence of PVC among the types of plastics in the reviewed literature (see Table 3), grouping plastics with similar properties reduces the contamination of waste streams and thereby facilitates recycling (Hopewell et al., 2009). Often incineration and landfilling are the most cost-efficient options when it comes to mixed waste streams, depending on the regional context and whether life-cycle costs are considered (Hopewell et al., 2009). More sophisticated source segregation or moving away from PVC altogether, or both, would be required to facilitate the circular economy.

Segregation is also essential for separating biohazardous medical waste from non-hazardous waste (e.g. packaging, catering trays and unused medical plastic products), which has implications for health and safety, as well as the environment. If waste is appropriately separated, the vast majority of it can be classified as general waste, with the rest being managed as hazardous (Mosquera et al., 2014). The reviewed studies suggest that economically developed countries such as Canada (Stall et al., 2013) and the Republic of Korea (Shinn et al., 2017) are managing this issue better than developing countries such as Burundi (Niyongabore et al., 2019a) and Iran (Taghipour and Mosaferi, 2009). In Iran, poor handling and disposal of medical wastes, for example mixing with domestic waste, open burning and use of unregulated dumps, have been highlighted (Taghipour and Mosaferi, 2009).

Source segregation and co-mingled recycling would have an impact on the success of material recovery facilities (MRFs) at sorting and separating the recyclates from other waste streams. While co-mingled collection is easier than source segregation, the latter is more cost effective and efficient (McGain et al., 2009b). However, after the collection stage, the reviewed studies barely distinguish between different types of recycling i.e. where the waste streams go once collected and how they are then processed and returned back to the system, to form a circular economy. This limited consideration of circularity highlights a broader issue within the waste management thinking where every step on the value chain is considered and valued within its own silo.

In the reviewed papers, landfilling and incineration were prominent in both developed and developing nations (see Table 4). Yet, differences in waste management strategies within the reviewed articles reflect a disparity between developed and developing nations in how they approach and prioritise waste management in general. In particular, the strategies used in developed nations, including recycling and source segregation, were closer to the circular economy principles than those in developing nations. This disparity is partly due to a lack of resources and competing priorities in developing countries (Agamuthu, 2003), as well as the additional burden of processing developed countries' exported waste (Liu et al., 2018). On the other hand, while less regulation in developing countries might be expected to facilitate more experimentation, in practice, limited R&D resources inhibit the investment-experience cycle and a lack of appropriate regulation can result in inadequate waste management systems (Mrayyan and Hamdi, 2006). The variety in approaches to plastic waste management on a global scale suggests that international cooperation is necessary to ensure equity of progress. The EU Strategy for Plastics in a Circular Economy recognises the strength in taking global action, given that the impacts of plastic waste affect the global commons and the benefits of improved waste management should be shared (European Commission, 2018).

Current criteria for prioritising waste strategies appear to be based on TRLs rather than on the circular economy principles. Even in developing countries, the commonly used Waste Hierarchy is not detailed enough to allow for the combination of multiple strategies, the sensitivities of specific contexts (Marshall and Farahbakhsh, 2013) or the consideration of circular economy principles (Fletcher and Dunk, 2018). For example, the Waste Hierarchy fails to discourage downcycling. If developing countries could 'leapfrog' the Waste Hierarchy's lower levels and move straight to the circular economy principles, it would help them to avoid lock-in.

#### 5. Conclusion

This review has identified the types of plastics and plastic products utilised and discarded in hospital settings, and explored

current and alternative waste management strategies, which have been analysed in light of their position on the Waste Hierarchy and the maturity of the technology involved. The key contribution of the paper relates to the need to address the increasing use of plastics within hospital settings (Chauhan et al., 2019) and to consider strategies for managing plastic waste in ways that align more clearly with the principles of the circular economy (Rizan et al., 2020).

The results of this study have been shaped by its scope. In particular, the boundaries of the literature search might have omitted some of the research exploring more innovative waste management strategies, due to both excluding studies about medical waste in non-hospital settings (e.g. dentistry or veterinary clinics) and excluding conference papers on quality grounds. The search has also privileged studies about waste management in hospitals rather than research on new technologies and practices that may be suitable for use in hospitals but have not yet been applied. Publishers' paywalls exacerbate the problem. Apart from extending the search and access to full texts, this work could be advanced in several directions explained below.

The WH-TRL framework suggests that, within hospitals, there are few waste management strategies in their infancy (see Figs. 1 and 2), showing potential for future research that investigates the barriers to the development of such innovations. The EU Commission sees innovation as a key element in transforming the treatment of plastics across a variety of sectors, recognising the need for large-scale investment in relevant research (European Commission, 2018). The mountain of plastic waste related to COVID-19 is an additional incentive to invest and innovate in this area (Prata et al., 2020).

Waste management strategies from non-medical contexts might bring in further innovative ideas to hospitals, with appropriate health and safety standards considered when transferring such innovations across sectors. For example, governments' bans and levies on microbeads, lightweight plastic bags, straws, cutlery and polystyrene food containers, have succeeded to some extent, encouraging manufacturers to innovate and users to accept alternatives (Schnur et al., 2018). Such policies incentivising both innovation and behavioural change across the system would be essential in the sphere of medical plastics.

At the systems level, designing and prioritising new waste strategies should include more than technological readiness. While the TRLs have been expanded to consider integration and systems readiness levels (Sausser et al., 2006), these are still restricted to technological aspects and fail to include the circular economy principles in associated business models (Mendoza et al., 2017). To maximise the value at the systems level rather than for particular organisations within supply-chain silos, policy-makers need to consider infrastructure, investment, societal aspects, financial viability of key industries, and political will.

At an institutional level, future enquiry should consider the processes preceding waste generation such as procurement practices and training. For example, there is considerable scope for more reduction and reuse. While reusing items in a clinical context presents obvious barriers, particularly in relation to cross-infection and contamination (Chauhan et al., 2019), some concerns regarding infection risk are not sufficiently evidenced, leaving potential for more reuse (Voudrias, 2018). Decisions to procure single-use instruments in medical settings as standard practice are also influenced by financial constraints impeding more expensive alternatives (Chief Medical Officer, 2017). Where reusing items is infeasible, excess waste could be avoided through reduction, for instance by wrapping sterilised instruments in a single layer of plastic wrap rather than a double layer (Webster et al., 2005), or by encouraging practitioners to open packs of plastic instruments only

when needed rather than pre-emptively (Connor et al., 2010).

The agency to improve hospitals' waste management strategies lies across a range of stakeholders, including hospitals' staff, companies supplying medical goods, organisations collecting and managing medical waste, and local and national governments who regulate the practices. Hospitals and other stakeholders should be rewarded for regularly trialling innovative waste management strategies. Given the socially and environmentally important functions of medical waste management, a special effort should be made to make innovations in this sphere open and compliant with the circular economy principles.

## Author contribution

**Carly A. Fletcher:** Conceptualization, Methodology, Investigation, Writing – Original Draft, Writing – Review & Editing, Visualization. **Rebecca St. Clair:** Writing – Original Draft, Writing – Review & Editing. **Maria Sharmina:** Conceptualization, Methodology, Writing – Original Draft, Writing – Review & Editing, Supervision, Project administration, Funding acquisition.

## 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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