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Recent advances and challenges in recycling and reusing biomedical materials

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Abstract

Medical waste has increased in the past 3 years as a result of the coronavirus disease 2019 (COVID-19) pandemic. This condition is expected to exacerbate due to the growing healthcare markets and aging population, posing health threats to the public via environmental footprints. To alleviate these impacts, there is an urgent need for medical waste management. This article highlights the drawbacks of current disposal methods and the potential of medical waste reuse and recycling, emphasizing the processes, materials, and chemistry involved in each practice. Further discussion is provided on the chemical and mechanical recycling of plastics as the dominating material in biomedical applications, and possible strategies and challenges in recycling and reusing biomedical materials are explored in this review.

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Recycling, Reuse, Waste management, Medical waste, Biomaterials, Circular economy.

Introduction

Healthcare waste is defined as the waste generated via medical procedures at healthcare or research facilities and laboratories [1,2]. Medical waste is divided into two categories: (i) hazardous waste, involving biological, chemical, radioactive, and/or physical footprints, and (ii) non-hazardous waste, constituting about 85% of waste generated from healthcare activities that are similar to domestic waste [3]. Improper medical waste handling and disposal may impose health risks on healthcare workers and the public [4]. This mainly occurs through the transmission of infectious or drug-resistant microorganisms, toxic exposure to chemical and pharmaceutical waste, and the release of air pollutants [3,4]. Soaring medical waste production as a result of the COVID-19 pandemic [5,6] is expected to be perpetuated by the projected growth of emerging healthcare sectors and the aging population, posing environmental hazards and causing illnesses in a significant number of people [7].

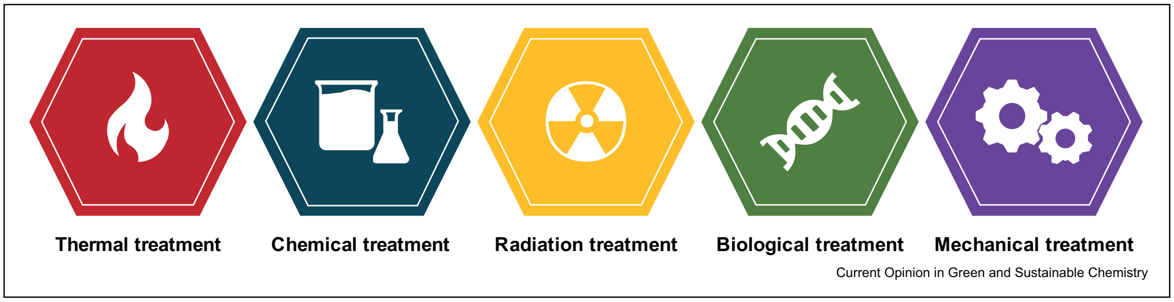
Figure 1 shows the current medical waste treatment methods, including thermal, chemical, radiation, biological, and mechanical treatments, where the thermal treatment is the most common technology worldwide [1]. The two most common thermal treatment methods to dispose of hazardous waste are incineration and autoclaving [4,8]. Undesirable emissions, such as dioxins, furans, and heavy metals, occur during incineration [9,10]. Also, some organic solvents used in the pharmaceutical industry, such as 2,2,2-trifluoroethanol, cause corrosion in incinerators [11]. With autoclaves, aside from the difficulties of handling mixed clinical waste or large and bulky materials [1,4,8], additional treatments may be required because of the untreated appearance of autoclaved waste, involving financial costs and adverse environmental impacts [4].

Overall, the environmental impacts and health risks associated with medical waste, as well as the shortcomings of current disposal approaches have increased the demand for recycling and reuse strategies as part of waste management. In addition, other factors such as reducing the reliance on natural resources, improving the accessibility of medical products, and increasing the financial gain for the health sectors motivate the utilization of these approaches [12]. In this article, we will review the recent advances in recycling and reusing biomedical materials, discuss challenges associated with each practice, and outline prospects for future research.

Reprocessing and reusing biomedical materials

Reprocessing and reusing medical materials and devices are common waste management approaches to increase economic and environmental benefits [7,13]. There are protocols and guidelines specifically designed for reprocessing and sterilizing multiuse medical devices, whereby health risks merely ensue in case these protocols are not rigorously followed [14]. Likewise, with strict considerations, the reprocessing of single-use medical devices (SUMDs) has been established and

Figure 1



Current medical waste treatment strategies [1].

supported in various countries, including Germany and the USA [15]. The ability of a target biomedical material to withstand cleaning, disinfection, and sterilization without undergoing any property change plays a significant role in selecting appropriate methods for reprocessing and reusing. Figure 2 demonstrates suitable sterilization approaches based on plastic material properties. The growing use of disposable devices has led to a shift from other biomedical materials, such as glass, metals, and ceramics, to plastics [16].

Sterilization can be divided into three categories: (i) thermal, (ii) radiation, and (iii) chemical sterilization [17]. Steam sterilization (autoclaving, limited to moisture-resistant materials) and dry heat sterilization are among the thermal treatments that are used for heat-resistant materials [16]. Autoclaving can cause corrosion in surgical alloys or rust in instruments [17]. Moreover, it has been reported that the repeated autoclaving of polyvinyl chloride (PVC), used in blood bags, causes plasticizer loss, molecular weight reduction, and increase in tensile modulus and yield strength [18].

In low-temperature sterilization methods, medical devices are radiated at varying wavelengths and penetration power. Electron beam, gamma, and X-ray radiations are used for low, medium to high, and high penetration needs, respectively [16]. Typically, plastics used in medical devices are susceptible to structural changes, including degradation, discoloration, and crosslinking during radiation sterilization [16,18]. This includes the gamma irradiation of PVC/polystyrene blends [19], polypropylene (PP) [20], polymethyl methacrylate [21], and polyethylene terephthalate fibers [22], as well as the electron beam sterilization of polylactic acid [23].

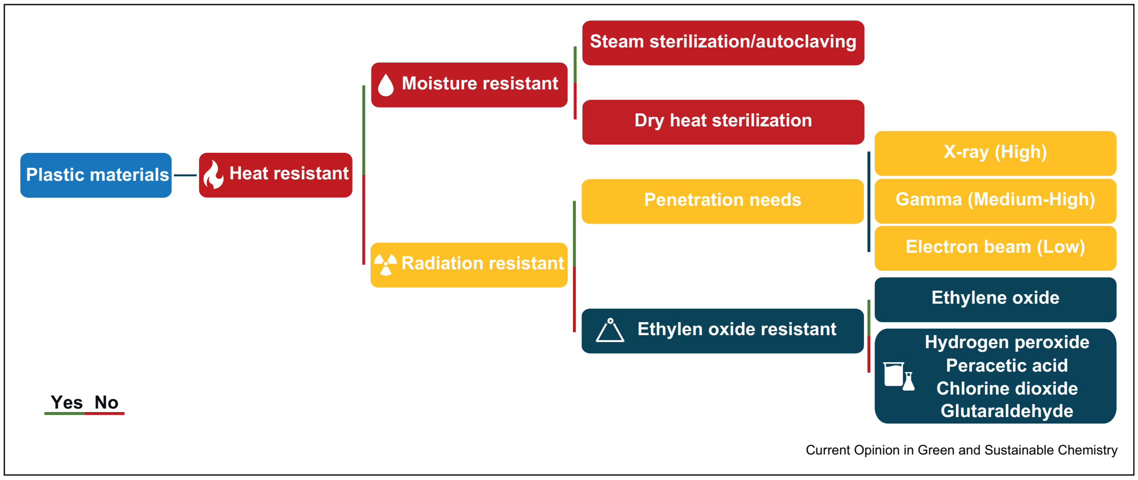
For radiation- and heat-sensitive materials, chemical agents, such as chlorine compounds, aldehydes (formaldehyde and glutaraldehyde), hydrogen peroxide, peracetic acid, and ethylene oxide (EO), are used as chemical treatments for disinfection and sterilization [16]. In this type of treatment, disinfection is typically conducted instead of sterilization [1]. It should be noted that different chemical treatments may affect the tensile strength of materials used in SUMDs, such as polyurethane (PU), latex, nylon, or polyethylene (PE) [24]. It has been shown that using EO as a low-temperature sterilization method renders PU catheters toxic, which requires a long aeration time to remove toxic residues [25]. Sterilization of PU electrophysiology catheters via the concurrent use of plasma and oxidative sterilants, such as vaporized hydrogen peroxide or peracetic acid, resulted in additive (antioxidant Irganox 1076) degradation or difference in coloration [25]. Moreover, antimicrobial nanostructured zinc-based coating in personal protective equipment (PPE) may improve disinfection, enabling the extended reuse of PPE via self-sterilization [26].

Overall, these studies show that reprocessing and reusing biomedical materials should be material specific. Moreover, after each sterilization or disinfection cycle, validation tests are needed to ensure that medical devices maintain functionality, and the risk of disease transmission by microorganisms is eliminated.

Recycling and recovery of biomedical materials

Recycling is conducted by converting a product to its materials and turning them into a new product, wherein the process suitability depends on the product components [7]. Most medical instruments are made from plastics, as they are cost-effective, durable, and flexible compared with steel, ceramics, and glass [27*]. It is therefore essential to recycle plastic-based materials, while a variety of non-plastic wastes have also been reported to be recyclable, such as stainless steel used in surgical instruments [28*], medical implants and dental prosthetics collected from the cremation industry [29], mercury from dental amalgams [30], and aluminum from waste pharmaceutical blister [31–34]. At least 12

Figure 2



Decision tree for plastic material sterilization method selection—Reproduced from the study by Sastri et al. [16], Copyright 2022, with permission from Elsevier.

United Nations Sustainable Development Goals are impacted directly or indirectly by plastic and microplastic pollution [35], which attests to the urgency of recycling plastic-based materials.

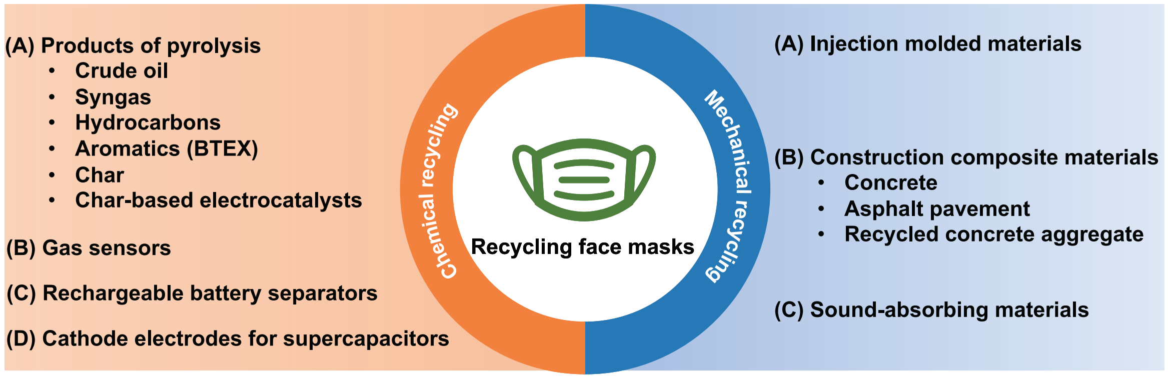
Several programs have been developed worldwide for plastic-based medical waste recycling. A recycling pilot was developed in the UK to downcycle PVC-based materials such as anesthesia masks, oxygen masks, and tubing into horticultural items [36]. Another PVC recycling program in hospitals is conducted by the Vinyl Council of Australia to remanufacture valuable items, including industrial hoses, from recycled PVC medical waste, such as oxygen masks and tubing, intravenous fluid bags, and suction tubing [37].

In general, plastic waste is recycled using primary, secondary, tertiary, or quaternary pathways. Primary recycling (also known as re-extrusion and closed-loop recycling) is limited to almost pristine waste and is generally exploited in the processing line, because the recycled products must have a similar quality to the original plastic [38,39]. Consequently, applying primary recycling to medical wastes may not be feasible. In secondary (mechanical) recycling, mechanical processes are used to recover plastic wastes. These processes, involving the sorting, washing, and extrusion of plastic waste, generally lead to the degradation of polymers [38]. Tertiary (chemical) recycling refers to the use of chemical processes to recover the petrochemical components of plastic wastes [38]. During quaternary recycling (or energy recovery), energy is recovered by waste incineration, and harmful emissions are inevitably produced [38], which is unsuitable for recycling medical waste. Effective energy recovery is not attainable in healthcare waste incinerators due to their small sizes [1]; however, by reusing incineration products, the environmental impacts of incineration may be reduced. For instance, replacing fine aggregates in concrete with incinerated biomedical waste ash results in improved strength and reduced permeability, while eliminating the necessity of landfilling the ash [40]. Considering the limitations of primary and quaternary recycling, mechanical and chemical treatments may be primarily considered for the recycling and recovery of biomedical materials.

Mechanical recycling of plastic-based biomedical materials

Mechanical recycling of medical waste has been the focus of several studies. Blue wrapping papers, made from PP used to wrap surgical instruments, are injection-molded into new medical devices without using additives. The mechanical properties of materials recycled through the injection molding of molten wrapping paper waste did not significantly change at varying melting temperatures, and the products withstood up to 10 disinfection cycles with preserved properties [12]. With the extensive consumption of PPE, such as surgical face masks during the COVID-19 pandemic, there has been an increasing interest in PPE recycling [41*] via mechanical and chemical recycling pathways to yield products for various applications (Figure 3). This includes developing sound-absorbing porous materials from PP-based face masks with comparable performance to commercial counterparts [42*], as well as the immense potential of using recycled face masks in construction applications [43,44]. Adding shredded face masks (SFM) to concrete resulted in negligible changes in compressive (about 5% increase) and tensile (about

Figure 3



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Recycling face masks via chemical or mechanical methods to yield a variety of products.

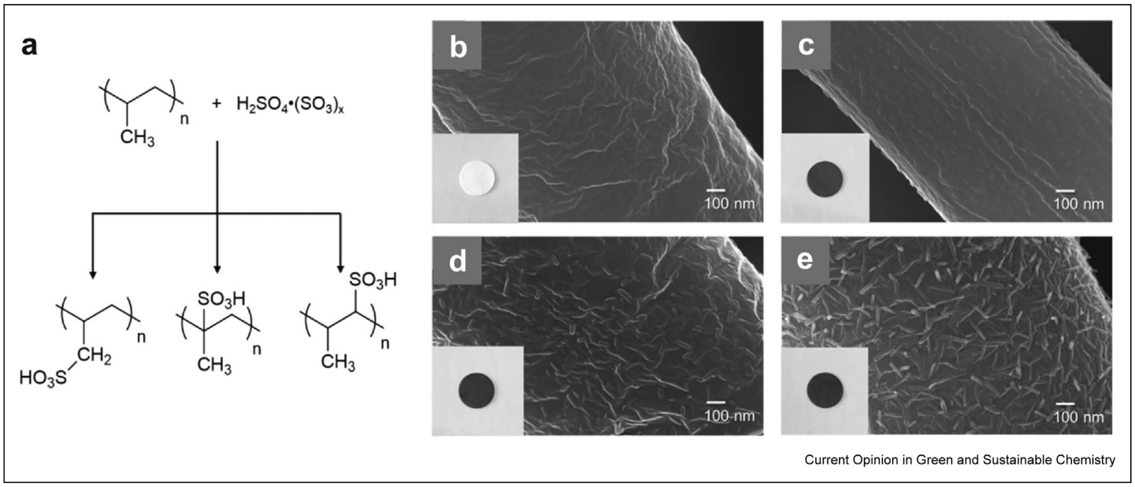
3% decrease) strengths, with preserved material stability under spalling and frost resistance tests [43]. Incorporating 1.5% of SFM into hot mix asphalt ameliorated the rutting resistance of asphalt pavement, resulting in 69% decrease in the rutting depth [45]. In another study, using 1% of SFM in recycled concrete aggregate (RCA) increased the unconfined compressive strength (by 17%) and resilient modulus (by about 4%), as the PP fibers reinforced RCA particles, rendering the final blend suitable for pavements base and subbase applications [44].

Chemical recycling of plastic-based biomedical materials

Tertiary recycling enables the treatment of contaminated and heterogenous plastics with minimal pretreatment [39]. Pyrolysis is a promising thermochemical treatment of medical waste, as it provides environmental advantages [46], including lower pollution and carbon footprint compared with other thermal treatments, and there is no requirement for the earlier separation of different waste plastics prior to pyrolysis [47]. This process has been applied to different types of medical waste to produce value-added materials [47–51]. Waste syringes made from PP were recycled via pyrolysis in a semi batch reactor, where the pyrolysis oil contained alkanes, alkenes, and aromatic rings, and the physical properties of it were close to the diesel fuel and petrol blend [48]. Syngas and C_{1-2} hydrocarbons were yielded from the catalytic conversion of disposable masks made from PP, PE, and nylon-6 over nickel/sulfur dioxide (Ni/SO_2) catalysts in a carbon dioxide (CO_2) reaction medium. In this thermochemical process, the conversion of long-chain hydrocarbons to methane and hydrogen on the Ni/SO_2 catalyst was significant, and the carbon monoxide (CO) formation was increased in the CO_2 medium [49*]. The catalytic fast pyrolysis of disposable masks has been used to produce high-value aromatics, including benzene, toluene, ethylbenzene, and xylene (BTEX) [50]. Without catalysts, branched hydrocarbons were yielded, whereas zeolite catalysts enabled the production of aromatic compounds, and higher BTEX selectivity was obtained in the catalysts containing larger pore sizes [50]. Also, activating and functionalizing char, as a product of face mask pyrolysis, with iron (Fe)-phthalocyanine and Ni-phthalocyanine has yielded electrocatalysts for oxygen reduction and hydrogen evolution reactions, respectively [51].

Other chemical processes may also enable tertiary biomedical material recycling. Recently, a process has been developed, whereby a simple chemical treatment on face masks resulted in a highly efficient separator for aqueous rechargeable batteries [52*]. In this process (Figure 4a), the middle filter layer of disposable masks made from PP-based nonwoven fabrics (Figure 4b) was treated with fuming sulfuric acid (FSA) for 2–6 min, changing the color to light brown and increasing the surface toughness (Figure 4c–e). During this reaction, the hydrophobic surface of middle filter was rendered hydrophilic with copious hydroxyl (-OH) and sulfonic acid (-SO_3H) groups, and the final separator improved the electrochemical performance compared with conventional glass-fiber based separators [52*]. In another study, a hydrothermal process was used to load zinc sulfide (ZnS) nanoparticles in a sensing substrate made from waste mask fibers, where the resulting composite was used as a gas sensor [53]. Compared with ZnS-loaded ceramic substrates, this gas sensor demonstrated 8.4–35.2 times higher sensitivity to different analytes, including formaldehyde, ammonia, hydrogen peroxide, and relative humidity (85%). This is attributed to the complete exposure of nanoparticles to target

Figure 4



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(a) Expected pathway for FSA-mediated PP chemical modification. Optical and scanning electron microscopy (SEM) images of **(b)** a mask filter, and sulfonated mask filters treated with FSA for **(c)** 2 min, **(D)** 4 min, and **(e)** 6 min—Reproduced from the study by Kim et al. [52*], Copyright 2021, with permission from Elsevier.

gases because mask fibers are highly permeable [53]. It has been shown that waste PP masks could be recycled into sulfur-doped porous carbon via sulfonation and carbonization methods, which is used as a cathode for supercapacitors [54].

Recycling PVC, as the primarily utilized plastic in terms of volume in medical devices [27,55], is challenging and imposes adverse environmental impacts, especially in the forms of air pollutants and chlorine, which contaminates recycling products and causes equipment corrosion [38]. These problems are addressed by introducing catalysts, hydrogen chloride inhibitors, or pretreatment processes to increase the efficiency of recycling procedures [38]. Promising techniques such as near-critical methanol (NCM) for PVC-medical waste treatment may be implemented, wherein efficient additive recovery and dechlorination efficiency of >90% have been obtained at 250 °C [56]. Aluminum has also been completely recovered from PVC plastic in waste pharmaceutical blisters via a hydrometallurgical method, wherein the waste is leached with hydrochloric acid [57].

Challenges and outlook in recycling and reusing medical waste

Medical waste recycling faces several challenges, including unstandardized sorting as well as health concerns regarding recycling infectious waste. Most hospital wastes are not infectious, rendering them suitable for recycling programs [58]. However, unstandardized medical waste sorting has led to the erroneous disposal of items as infectious waste [59], imposing unnecessary costs associated with infectious waste treatment [4]. This challenge might be addressed using machine learning algorithms, as they have been utilized to sort and classify wastes for different industrial applications, such as plastic waste, bottle, and municipal solid waste recycling, with >90% accuracy [60]. Training healthcare workers on waste management may improve their practices in biomedical waste handling and disposal [61,62]. Furthermore, social and ethical concerns stemming from the health risks of infectious medical waste recycling should be addressed by raising public awareness and implementing strict protocols for medical waste recycling [27*]. In addition, economically feasible processes should be developed for plastic recycling, and the design of plastic-based materials should satisfy the feasibility of efficient recycling by following healthy design practices [27*]. Using bio-based plastics in medical applications is another alternative that may lower environmental impacts [63] and, with further exploration, might lessen recycling costs associated with the petroleum-based counterparts [64].

Conclusions

Environmental and public health concerns regarding the rapid increase in medical waste generation and the drawbacks of current disposal methods may be addressed by practicing recycling and reuse programs. Compared with current disposal methods, reprocessing and reusing medical devices are environmentally and financially beneficial. Still, established protocols should be strictly followed to eliminate the risk of contamination. Also, preserving the functionality and original properties of materials needs to be considered in selecting reuse methods. Recycling and recovery are other approaches that may enable the efficient management of biomedical material waste. Nevertheless, challenges associated with sorting, designing, and sterilization are ahead of recycling programs. In summary, efforts should be devoted to allocating financial and technological resources, enabling sustainable waste management programs in healthcare sectors through recycling and reusing biomedical materials.

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 article.

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