

Impacts of COVID-19 Outbreak on the Municipal Solid Waste Management: Now and beyond the Pandemic

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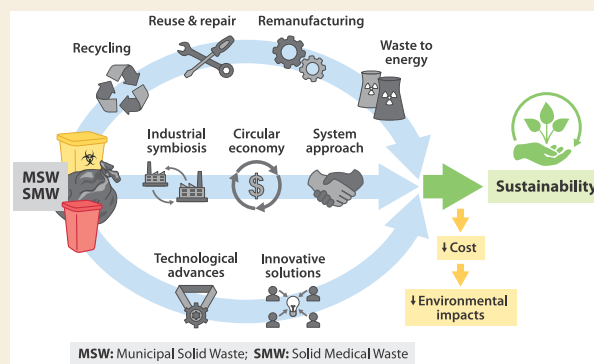


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Supporting Information

ABSTRACT: The COVID-19 pandemic disrupted the municipal essential services, including municipal solid waste (MSW) management. This study has reviewed the literature on MSW and solid medical waste (SMW) management systems, waste management initiatives specific to this pandemic, as well as their impacts now and beyond. Waste segregation and separate treatment of waste streams play important roles in reducing the environmental, health, and social impacts of waste and waste management. The global warming potential of MSW and SMW were found to be varied from -0.64 to 520 kg CO₂ equiv/tonne and -52.1 to 3730 kg CO₂ equiv/tonne, respectively, which widely depend on the sterilization and disposal processes. Similarly, MSW and SMW disposal costs varied from 90 to $\$242$ /tonne and 12 to $\$1530.0$ /tonne, respectively. Various changes made to waste collection and management because of the COVID-19 pandemic affected waste segregation and recycling. Since the start of the pandemic, various sectors, including the food, waste management, and healthcare sectors, relied on the increased use of single-use plastics to prevent transmission of COVID-19. An environmentally friendly alternative (biodegradable/compostable) to widely used single-use plastics is desired for easing waste management problems. Although various initiatives are underway to manage growing volumes of MSW and SMW, while controlling the spreading of infectious diseases, the movable grate incineration technology coupled with an adequate disinfection process presents a potential solution in managing the COVID-19 waste challenges. The proper disinfection method and technological choices can mitigate the risk of spreading infections and can improve the waste management system's sustainability, especially the contaminated waste.



INTRODUCTION

Municipalities provide waste management services to their residents to meet one of their basic/essential needs— safe and timely collection of waste. These vital services are often interrupted by disease outbreaks, as seen with the novel coronavirus (COVID-19), which can result in the improper storage and disposal of waste. The buildup of wastes often contaminated with organic matter, micro-organisms, and biological fluids can lead to sanitary problems or even collapse entire municipal waste management systems¹ and resultantly cause frustration and feelings of distress.^{2,3} Poorly managed waste can result in social, environmental, and health consequences including an increased risk of spreading infectious diseases, especially during pandemics like COVID-19.⁴ Proper management of municipal solid waste (MSW) and solid medical waste (SMW) is crucial to controlling the spread of infectious diseases.^{1,5,6} SMW is generally disinfected and then treated as general MSW by municipalities. For example, the disinfected SMW managed along with MSW is usually landfilled in Canada, but management varies by jurisdiction.⁷ The potential severity of disease transmission through improper handling of waste depends on both the category of waste and local vulnerability.⁸ In 2020, COVID-19

disrupted and challenged municipal waste management systems, which were oftentimes already operating unsustainably, without the ability to safely manage additional volumes of waste and other obstacles presented by the pandemic.⁹ COVID-19 virtually devastated every sector of human activities, including education, economy, food, and healthcare systems, resulting in related consequences to MSW management systems.^{6,10} For example, in Europe, 80% of companies in the textile and apparel sector were laying off their workers because sales were cut in half due to the pandemic.¹¹

The outbreak of COVID-19 in March 2020 created several unforeseen pressures on municipal waste management. In most jurisdictions, services were permitted to continue despite various lockdown and curfew measures put in place to thwart transmission of the virus. Waste management personnel who

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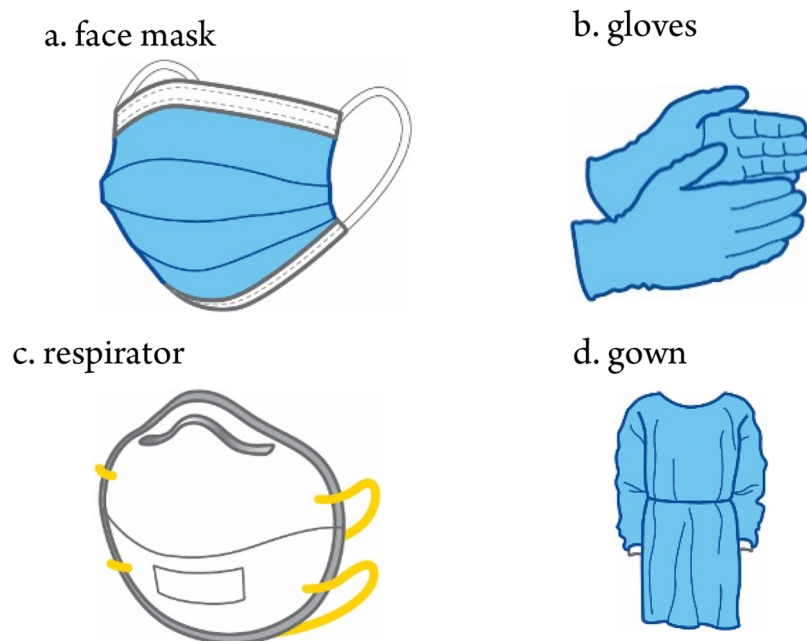


Figure 1. Commonly used PPE.

continued to work throughout the pandemic were more likely to be exposed to the virus through close contact with other employees or contact with contaminated materials.¹² At the same time, municipal services saw an increased rate of absenteeism, straining their workforce and affecting their operability.^{13–17} Meanwhile, as people changed their daily lifestyle to work from home, typical waste trends and volumes also changed, requiring adjustments to program delivery.¹ Municipal waste programs also had to contend with an influx of used personal protective equipment (PPE) (Figure 1), often made of single-use plastics, including masks and gloves, as well as single-use and recyclable plastics used to prevent contamination of foodstuffs and other consumer goods. Globally, every month, 129–210 billion disposable masks and 65 billion disposable gloves are used.^{18–20} Further, waste has skyrocketed in the healthcare sector during the COVID-19 pandemic.^{5,21,22} Improper management of medical waste has adverse impacts on society.²¹ In the recognition of the risks and challenges associated with waste management during a global pandemic, sources have advised jurisdictions to ensure adequate precaution for waste collectors, making adjustments to recycling programs^{23,24} and in planning for the safe treatment of increased quantities of medical waste in order to ensure public safety and to abate the dissemination of infectious diseases.^{2,6,25}

Although numerous initiatives are underway to phase-out single-use plastics to mitigate environmental pollution from waste plastics, demand for some single-use plastic products has surged due to the COVID-19 outbreak. The increased use of PPE has created an enormous demand for single-use plastic products, including face masks, face shields, gloves, head mobs, gowns, and shoe covers, all of which require safe disposal, thus creating problems for downstream waste management.²⁶ In addition, various levels of government have mandated the use of face masks in public places and businesses to reduce the spread of COVID-19.^{27–30} Polypropylene melt-blown nonwoven fabric is the primary filter material used in a medical mask. However, masks are

also produced from polystyrene, polyethylene, polycarbonate, and polyester.³¹ The increasing production and consumption of single-use plastic products during the COVID-19 pandemic could have long-lasting adverse impacts on the environment and global goals to reduce reliance on single-use materials and circular economy initiative.

A 70% increase in waste generation is expected by 2050 (3.4 billion tonnes) from the 2016 level (2.01 billion tonnes) in the world due to the population and urban growth.³² The waste generation rate (36.1 tonnes per person/year) is reported to be the highest in Canada and produced 1.33 billion tonnes of waste in 2017.³³ Residual pathogens in medical waste make waste management problematic as the waste must be decontaminated before being disposed of.³⁴ Various efforts and management strategies are being implemented to manage the surging waste during this pandemic; however, technological advances in MSW and SMW management, their environmental, economical, and societal impacts are yet to be synthesized. This study compiles waste management initiatives that are being implemented during the COVID-19 pandemic to discuss their advancement and their environmental, economical, and societal impacts.

METHODS

Various academic search engines (ScienceDirect, Google Scholar, SpringerLink, Mendeley, Scopus platforms, Worldwide science, etc.), as well as online information (google, news articles, reports, Web sites) were used to assemble literature related to MSW and SMW management in prepandemic and pandemic periods. MSW, SMW, COVID-19 waste, healthcare waste, waste management technologies, contaminated waste management, life cycle assessment, environmental impacts, and economic and societal impacts were used as keywords. Based on the initial screening (e.g., titles and a brief check of abstracts), 141 articles were collected and grouped according to their categories (introductory, environmental, economic, societal). It is worth mentioning that the literature was searched in English only. The collected literature was then synthesized (126 articles) in the corresponding sections of in this article, while the irrelevant articles were removed from the corresponding folders.

COVID-19 OUTBREAK AND MSW MANAGEMENT

The COVID-19 pandemic has led to unprecedented challenges in handling MSW, including the influx of SMW and single-use plastic PPE in waste streams.^{35–37} Contact with contaminated surfaces is one common mode of infectious disease transmission and plays a crucial role in spreading infectious diseases.³⁸ Consequently, usual waste management practices have been augmented due to the pandemic to reduce interaction between site staff and the public, thus reducing the risk of spreading infectious diseases.^{36,39,40} However, a recent study has argued that fomites play a small role in COVID-19 transmission, and there has been an overemphasis on cleaning surfaces and disinfecting packages.⁴¹

Municipal waste management facilities are typically designed to handle a predictable and steady waste flow rate, with some seasonal variations on waste volume. During the COVID-19 pandemic, the volume of medical waste dramatically increased, while increases and decreases in MSW volume have been reported in different regions.^{11,37,42} For example, during the COVID-19 pandemic, New York has generated 3.3 and 13.3% more MSW and organic waste, respectively.⁴⁰ On the other hand, Catalonia and Barcelona have also produced 16.7 and 25.0% less municipal waste, respectively.¹¹ The generation of MSW also declined in some provinces of China.⁴³ In Wuhan, the generation of medical waste increased from 40 to 240 tonne/day due to this pandemic, surpassing the city's maximum incineration capacity (49 tonne/day).^{42,44} Consequently, the city deployed 46 mobile waste management plants to handle SMW.³⁷ In Romania, increasing healthcare waste generation has been reported, where medical and quarantine waste contributes 10.9 and 17.2% to total waste flow, respectively.⁵ An increase in the generation rate of agricultural waste has also been reported in some regions, due to disruptions in supply chains and processing facility shutdowns causing spoilage of perishable foods.^{39,45}

The residential waste generation rate noticeably increased in Ontario, Canada (15% for garbage and 20% for green bin waste, while waste in blue bins remained static) but declined in commercial sectors.⁴⁶ Similarly, a decline in commercial waste in other municipalities/countries has also been reported.⁴⁷ For example, commercial waste generation decreased to 57% of normal levels in Tokyo due to business closures and lockdown protocols; however, a 110% increase in household waste was reported.⁴⁷

The increase in MSW results from several different causes and effects during the COVID-19 pandemic. The enforcement of lockdown protocols forbidding in-person dining has led to an increased use of single-use plastics for packaging of takeout food and food delivered to residences.²⁶ The annual growth of PPE use and resulting disposal is estimated to be 20% (relative to pandemic period, i.e., 2020) even in the postpandemic period and may continue up to 2025.^{48,49} It is estimated that PPE production needs to be increased by 40% globally to meet the rising demand.⁵⁰ Consequently, healthcare waste is expected to continue to rise until the pandemic is over or even in the postpandemic period, as the global population adjusts to a new normal.

Commonly used disinfection and contaminated waste management technologies are autoclaving, microwave treatment, plasma treatment, and incineration (Table 1). The choice of technology used to disinfect contaminated waste

Table 1. Waste Disinfection/Management Technologies Being Used to Disinfect SMW during the COVID-19 Pandemic

treatment	ref
high-pressure steam sterilization (121 °C, 110 min)	25
high-temperature pyrolysis (540–830 °C)	53
high-temperature incineration (800–1200 °C)	53,54
incineration (>1100 °C)	48
double-chamber incineration (primary chamber 750–980 °C temperature, while the secondary chamber is designed to operate at a temperature of at least 1100 °C)	55
chemical disinfection:	
sodium hypochlorite (NaOCl), chlorine dioxide (ClO ₂), ultraviolet irradiation, ozone are used for liquid waste	54
H ₂ O ₂ (>0.5%); ethanol (>75%), isopropyl alcohol (>70%), formaldehyde (>0.7%), povidone iodine (>0.23%), sodium hypochlorite (>0.21%), irradiation for 60 min	56
microwave technology (177–540 °C)	48
deep burial (1–2 m, topsoil cover 1 and 2 m above the groundwater level)	47

depends on technical, environmental, and economic factors, as well as social acceptance.⁵¹ Since the outbreak of COVID-19, the sudden surge of waste flows swamped the current waste management facilities.^{25,26} In the USA, the estimated COVID-19 waste generation was 530 million tonnes per year.⁴⁸ In Canada, COVID-19-related plastic waste generation from PPE is expected to be 63,000 tonnes per year.⁵² SMW generation rate varied from 350% in Spain¹¹ to 600% in Wuhan, China, depending on the severity of the pandemic.^{26,42} Table 2

Table 2. Estimated Healthcare Waste Generation Rate before and during COVID-19 in Selected Municipalities/Province (Healthcare Waste Includes Both SMW and Liquid Waste Streams)

municipality/ city	waste generation rate, tons/day			increase (%)	ref
	before COVID- 19	during COVID- 19			
Bangkok	27	160		493	57
Ha Noi	26	154		492	57
Jakarta	35	212		506	57
Wuhan	40	240		600	42,44

depicts the waste generation rates before and during the COVID-19 epidemic in various municipalities/regions. The healthcare waste generation was found to be the highest in Wuhan (600%) and the lowest in Ha Noi (492%) among the reported cities. It appears that the change in healthcare waste generation during the pandemic depends on the severity of COVID-19 in the region, number of hospitalizations, and the population density.

Various strategies are being implemented to manage the surge in COVID-19-related healthcare as well as MSW. In the European Union (EU), contaminated waste (face mask, gloves, tissues) is required to be double-bagged.¹¹ China has directed hospitals to use double-layered medical waste collection bags, which must be labeled as COVID-19 waste, and the surface of the bags has to be disinfected with alcohol.²⁵ China has also recommended handling of COVID-19 waste by personnel with specialized training to handle contaminated waste.²⁵ In Germany, takeout food containers

were treated as hazardous waste during COVID-19, which were usually considered as recyclable waste.¹¹

The World Health Organization (WHO) recommends onsite segregation and collection of noninfectious waste of healthcare systems as MSW, in strong black plastic bags during COVID-19,⁵⁸ which contributes 80–90% to total waste.^{8,35,54} Households with infected members are directed to limit the use of separate waste streams for organic material and recyclable goods, which has also stimulated the use of single-use plastic bags as well as generating a mixed-waste stream and creating additional logistical problems.¹¹ For safe handling of contaminated waste during the COVID-19 pandemic, a generalized approach has been proposed (Figure 2).²⁶

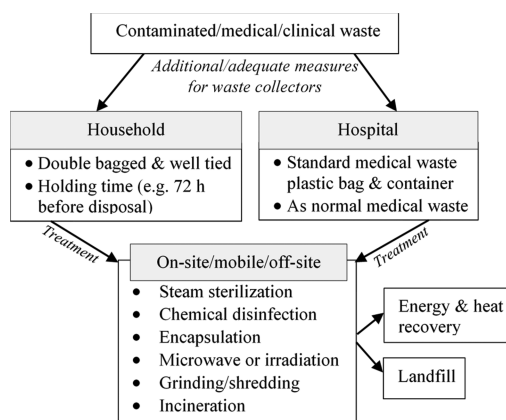


Figure 2. Contaminated waste handling approaches during COVID-19. Reproduced from ref 26 with permission. Copyright 2020 Elsevier.

The surge of waste has forced different countries to modify their waste management systems. For example, Spain allowed co-incineration in cement plants if necessary, and Norway permitted changes in landfilling.¹¹ However, China preferred onsite and mobile treatment (high-temperature incineration) of contaminated waste due to its flexibilities.^{25,26} Onsite incineration (23 incinerators are in operation in hospitals) of SMW has also been reported in Romania.⁵ On the other hand, the UK has increased their temporary storage capacity of MSW to manage increasing waste during COVID-19.⁵⁹ The recycling of sharp medical waste like needles/syringes in the steel industry (co-incinerated with coke) has also been reported in Australia.⁶⁰

Usually, most MSW is sent to landfills in both developed and developing countries in pre-pandemic periods, except for a few developed countries (Japan, Denmark, Sweden).³⁵ In developed countries, incineration is reported to be the primary waste management process for MSW, followed by landfilling and resource recovery, while in developing countries, the primary method is landfilling.³⁵ Japan sends only 4% of her MSW to landfill sites, whereas 74 and 17% is incinerated and recycled, respectively.⁶¹ A lower rate of landfilling has also been reported in some European countries (such as Denmark, Finland, Norway, and Sweden), where more than 50% of MSW is incinerated for energy recovery.⁶² In the UK, only 20% of the biodegradable portion of MSW was sent to landfilling in 2018.⁶³ However, more than 50% of MSW is sent to landfill in the USA and 95% in Canada.^{64–66} In many developing countries (Bangladesh, Brazil, India, Indonesia,

China, Thailand, etc.), a major portion of MSW is sent to the landfill.^{35,67} For example, in India, 70% of MSW is sent to landfill.⁶⁸

Changes to MSW management have been implemented in both developed and developing countries because of the COVID-19 pandemic³⁵ to ensure adequate protection against the transmission of the virus. For example, cities/regions/countries have temporarily stopped or reduced their waste recycling programs and waste segregation due to the pandemic,^{11,69,70} thereby reducing the sustainability of the waste management system.^{71–73} The scarcity of landfill sites and concerns about greenhouse gas (GHG) emissions and leachate have also led to the search for alternate disposal technologies. Some regions lack a COVID-19 MSW management strategy. For example, strategies are lacking for managing the COVID-19-related solid waste in Nigeria.⁷⁴ Although a coordinated waste collection system is reported to be effective in an area which lacks municipal waste collection service, especially in slum areas,⁷⁵ the pandemic has disrupted those initiatives. Acknowledging the informal economy and primary stakeholder's involvement is crucial to a sustainable waste management strategy.^{74,76} The hierarchy of zero waste can be useful for the stakeholder in outlining the waste management strategy to abate GHG emissions (Figure 3).⁷⁷

ENVIRONMENTAL AND ECONOMIC IMPACTS OF SOLID WASTE MANAGEMENT SYSTEMS

The increased use of single-use plastics during the pandemic has adverse effects on MSW management and creates unintended environmental concerns. For example, the energy consumption drastically increased in managing medical wastes (healthcare waste from hospitals and personal care from residence) and thus the environmental footprint.^{6,26} Emissions from the SMW incineration depend not only on the categories of the waste but also on the type of incinerators and operating parameters.^{78–80} For example, Van et al.⁸¹ used a wet scrubber (using 20% NaOH solution) and stack for gas cleaning; however, a bag filter and two stages of wet scrubber were adopted by Xie et al.⁷⁸ Usually, SMW consists of various types of plastics. The quality of waste streams depends on their compositions, especially the MSW, and thus the production of flue gas/syngas.⁷⁹ Among the different plastic waste management technologies, incineration is identified to be the second best, while recycling is noted to be the best in terms of environmental impact.⁸² A higher recycling rate improves the sustainability of waste management systems.^{72,73,83} However, incineration becomes a common practice for contaminated plastic waste to mitigate infectious disease from waste handling.

The GHG emissions from the incineration of various waste streams in different countries/regions are presented in Supporting Information, Table SI-1. The concentration of CO₂ in the flue gas from the incineration process varied from 7.1 to 9.8%.⁸⁴ The emission limit (CO, SO₂) is found to be the highest in Vietnam followed by the US and China. On the other hand, HCl and NO_x emission limits were highest in Japan. However, the measured emissions were greater than the specified limits. This variation might be the result of the selected technology. Widespread incineration of SMW or MSW in a densely populated area might be problematic because of the emission of pollutant gases.⁸⁰ A wide variation in the composition of MSW was also observed in the review literature. The organic waste contributed 28–64%, and

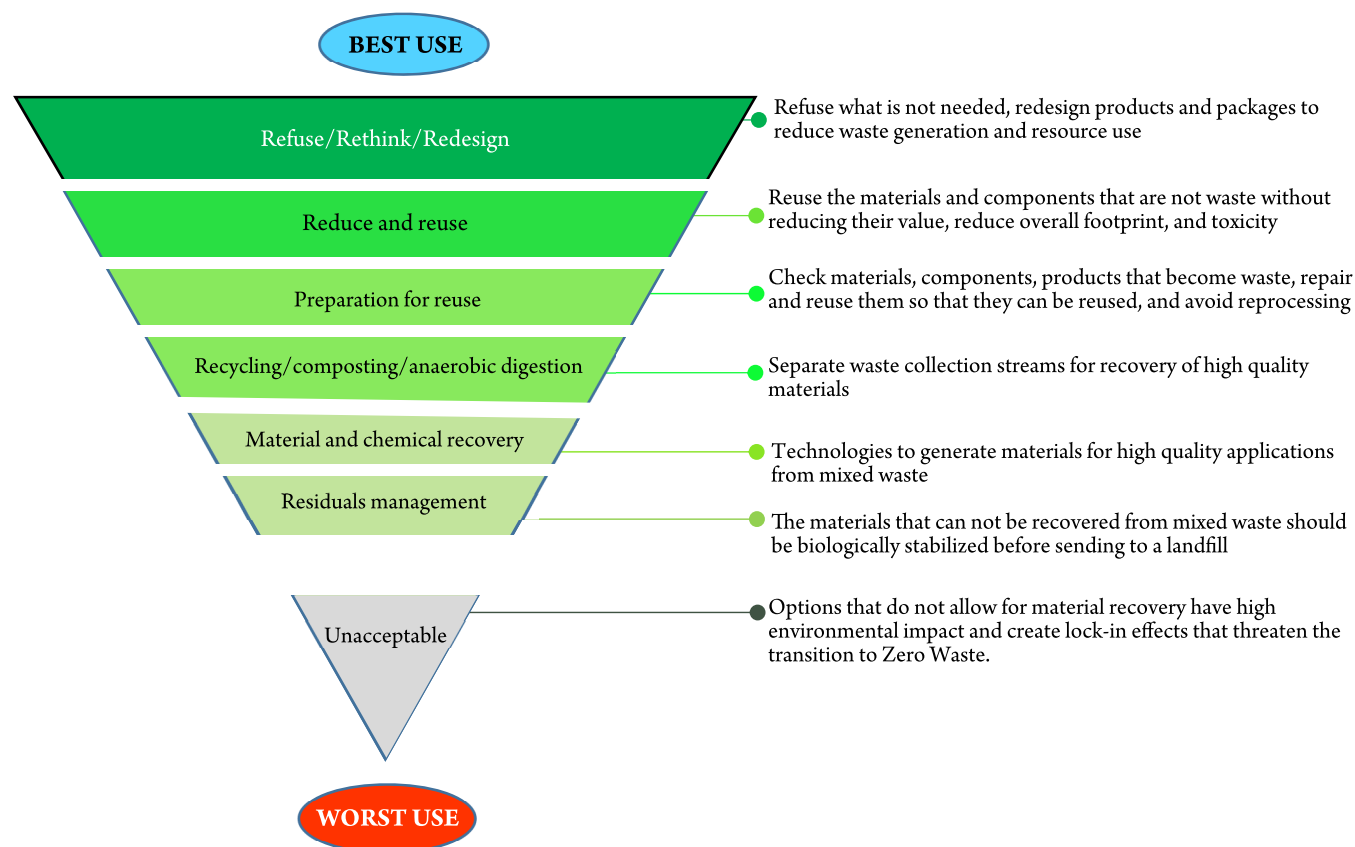


Figure 3. Hierarchy of waste management. Reproduced from ref 77. Copyright 2019 Zero Waste Europe.

plastics contributed 8–20% to total MSW (Table SI-2). A wide variation in pollutant gas emissions is observed because of the difference in technology and gas cleaning methods applied in the incineration process as well as the composition of waste streams, which varies depending on the countries/regions.^{80,85}

A wide range of environmental impacts is reported for different waste management systems (Table 3). These variations resulted from the composition of the waste stream, type of waste, management systems, energy recovery system, system boundary, sources of energy used in the waste management processes, etc.^{86,87} For example, in China, electricity from coal-fired power plants is used in waste management, whereas in Brazil, electricity from hydropower is used, and thus the same two waste management technologies using the same amount of electricity would have different environmental impacts because of the energy source.⁸⁷ The environmental impact of MSW also depends on the method of disposal.^{88,89} For example, incineration and landfilling produces 0.53 tonne CO₂ equiv and 10.84 tonne CO₂ equiv per tonne of MSW, respectively.⁸⁸ The environmental impacts of waste management were reported to be the highest for uncontrolled landfilling of MSW and the lowest for incineration of the residual portion of MSW, with the remainder going to landfills. The inclusion of incineration with composting of the wet organic portion and recycling of the recyclable portion was environmentally preferable.⁸⁶ On the other hand, anaerobic digestion of organic waste was preferred compared to composting.⁶²

Several authors argued that a portion of environmental pollution and the economic burden of SMW management

could be offset by heat and energy recovery from the incineration system.^{87,90} Among chemical disinfection, steam sterilization, and pyrolysis process, steam sterilization and chemical disinfection had the highest environmental impacts and the lowest economic burden, respectively.⁸⁷ In contrast, chemical disinfection combined with pyrolysis and landfilling of SMW is a better option compared with incineration combined with landfilling or direct landfilling.⁹¹ Zhao et al.⁹⁰ argued that environmental impacts could be offset if the appropriate measures are taken during the waste management process, such as energy recovery. The energy recovery also depends on the type of waste, embodied energy, energy recovery efficiency, and incineration parameters.^{26,60,90} Figure 4 represents the embodied energy and energy recovery from various waste management stages (plastics).²⁶ The demand and supply of recovered energy and heat have to be balanced to successfully implement the pandemic waste incineration process, while social acceptability can play a crucial role.

Plastics have greater embodied energy than paper or wood^{92–94} and thus have higher energy recovery efficiency,²⁶ and the recovered energy offsets a portion of the environmental impacts. Other impact categories (eutrophication, carcinogens, respiratory inorganics, etc.) were also greater in the case of steam sterilization and incineration compared with chemical disinfection and incineration.⁸⁷ In contrast, chemically disinfected waste landfilling has a higher environmental burden compared with steam-sterilized waste landfilling in Brazil.⁹⁵ This contradictory outcome resulted mainly because of the source of electricity that was used in the waste treatment process (usually, in China, electricity generates from coal, but hydropower is used to generate electricity in

Table 3. Environment Impacts of SMW and MSW Management^a

waste type	technology	database/method	impacts/tonne					WD	remarks	ref
			GWP	OD	FFD	AP	WD			
SMW*	incineration	GaBi	10.6	1.00×10^{-14}	1.84×10^{-04}	2.24×10^{-06}	1.52×10^{-04}		60	
SMW	incineration	Ecoinvent	1190.0	-	-	-	-	0% ER	90	
SMW	incineration	Ecoinvent	682.0	-	-	-	-	15% ER	90	
SMW	incineration	Ecoinvent	-52.1	-	-	-	-	30% ER	90	
SMW (mixed)	steam sterilization and landfilling	Ecoinvent	461.0	-	-	-	-	0% ER	90	
SMW (mixed)	steam sterilization and landfilling	Ecoinvent	451.0	-	-	-	-	10% ER	90	
SMW (mixed)	incineration	spreadsheet	688.5	-	-	-	-	ash landfilled	102	
SMW	pyrolysis and sanitary landfill	ReCiPe	1260.0	5.05×10^{-06}	182.37	2.60	71.87	sanitary landfilled	87	
SMW	steam sterilization and incineration	ReCiPe	3730.0	6.87×10^{-06}	429.75	5.22	109.30	ash landfilled	87	
SMW	chemical disinfection and incineration	ReCiPe	800.7	2.21×10^{-06}	151.30	0.95	33.31	ash landfilled	87	
MSW	incineration	SimaPro (Impact 2002+)	-0.648	-1.87×10^{-09}	-	-0.0037	-	ash used as a building material	103	
SS	incineration	SimaPro (Impact 2002+)	0.865	4.33×10^{-08}	-	0.0031	-	wastewater collected to WWTP	103	
MSW and SS	co-incineration	SimaPro (Impact 2002+)	-1.44	8.71×10^{-09}	-	-0.0035	-	ash landfilled, building materials	103	
MSW	incineration	GaBi (EDIP 97)	271.0	-	-	-0.748	-	ash landfill	104	
MSW	landfill	GaBi (EDIP 97)	502.0	-	-	-0.302	-	ER	104	
MSW (mixed plastic)	gasification-pyrolysis	SimaPro (ecoinvent)	1870.0	-	-	2.43×10^{-05}	-	ER	105	
MSW (mixed plastic)	incineration	SimaPro (ecoinvent)	0.898	-	-	-6.57×10^{-04}	-	ER	105	
MSW (mixed paper)	gasification-pyrolysis	SimaPro (ecoinvent)	1560.0	-	-	9.86×10^{-05}	-	ER	105	
MSW (mixed paper)	incineration	SimaPro (ecoinvent)	1030.0	-	-	-5.27×10^{-05}	-	ER	105	
MSW	composting and landfilling	SimaPro (ecoinvent)	376	-	-	3.2	-	no ER	106	
MSW	landfilling	SimaPro (ecoinvent)	2240.0	-	-	24.6	-	no ER	106	
MSW	landfilling	SimaPro (ecoinvent)	766.9	2.78×10^{-06}	-	1.2	-	ER	107	
MSW	incineration	SimaPro (ecoinvent)	-121.6	-2.47×10^{-05}	-	-2.9	-	ER, ash landfilled	107	
MSW	composting, incineration, landfilling	SimaPro (ecoinvent)	178.9	2.02×10^{-05}	-	-0.2	-	ER	107	
MSW	composting, recycling, incineration, landfilling	SimaPro (ecoinvent)	-153.1	1.93×10^{-05}	-	-1.0	-	ER	107	
MSW	landfilling 32.7%, incineration 41.2%, recycling 17.5%, composting 8.6%	-	1076.0	-	-	-	-	ash landfilled, no ER	108	
MSW	landfilling 54.7%, incineration 40.7%, recycling 3.4%, composting 1.2%	-	487.9	-	-	-	-	no ER	108	
MSW	landfilling 7.3%, incineration 57.6%, recycling 31.5%, composting 12.9%	-	211.3	-	-	-	-	ER	108	
MSW	AD (food waste, garden waste) recycling and incineration	-	-142.3	-	-	-	-	ER	108	

^aSMW, solid medical waste; MSW, municipal solid waste; SS, sewage sludge. *Syringe; GWP, global warming potential (kg CO₂e/tonne); OD, ozone depletion (kg CFC-11); FFD, fossil fuel depletion; AP, acidification potential (kg SO₂e/tonne); WD, water depletion (m³); ER, energy recovery; WWTP, wastewater treatment plant; AD, anaerobic digestion; EDIP, environmental design of industrial products.

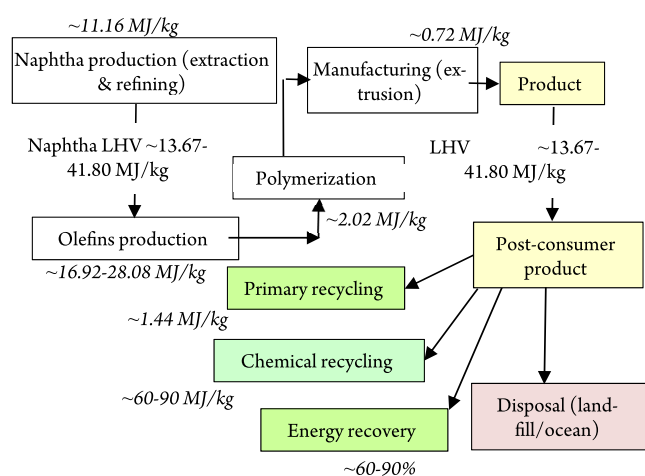


Figure 4. Energy flows in different stages of a product without transportation. Reproduced from ref 26 with permission. Copyright 2020 Elsevier.

Brazil).⁸⁷ In addition, the composition of MSW may also have played an important role in the resulting environmental impacts.

The waste management cost is also reported to be dependent on the adopted technology or type of waste and the location of treatment/disposal (Table 4). For example,

Table 4. Waste Management Systems and Waste Management Cost

waste	management process	cost, \$/tonne waste	remarks	source
SMW	pyrolysis	293.4	sanitary landfill after pyrolysis	87
SMW	incineration	263.3	chemically disinfected waste incinerated; ash landfilled	87
SMW	incineration	454.7	steam-sterilized waste incinerated, ash landfilled	87
SMW	landfilling	1100.0	chemically disinfected waste landfilled	95
SMW	landfilling	1530.0	steam-sterilized waste incinerated	95
MSW	landfilling	12.0	microwaved waste landfilled	95
MSW	incineration	-19.9	energy recovery, ash used as a building material	103
SS	incineration	50.0	energy recovery, wastewater send to WWTP	103
MSW and SS	co-incineration	-31.6	energy recovery, ash send to landfill/building materials	103

^aMSW: municipal solid waste; SMW: solid medical waste; SS.: sewage sludge.

airflow controlled (AFC) incineration was reported to be suitable for a small-scale operation to reduce MSW management costs.⁸¹ The higher recycling rate reduces waste management cost.⁸³ In China, SMW incineration cost is \$281.7–\$422.6 per tonne, whereas the MSW incineration cost is \$14.1 per tonne.⁴² Consequently, the surge of medical waste has put extra pressure on municipalities' waste management budget around the world. However, in Canada, the MSW disposal cost is \$90–\$242 per tonne, where most of her MSW is sent to the USA for landfilling, and the tipping fees are the main contributor to the total disposal cost.⁹⁶ The waste management cost depends on the waste stream and waste

management systems and also on the energy recovery and disinfection method used.

ONGOING EFFORTS IN MSW MANAGEMENT

Numerous efforts are underway in the development process of PPE to protect frontline workers against COVID-19 and reduce the waste management problems associated with the COVID-19-related waste.⁹⁷ China has formed a multisectoral team to safely manage surging healthcare waste during COVID-19.²⁵ Antiviral face mask filters are also being developed to enhance the reusability of conventional masks (such as surgical and N95 masks), which are not normally antiviral.⁹⁸ For example, salt^{98,99} and copper ions¹⁰⁰ are being used in the antiviral face mask development process. For quick decomposition of COVID-19 waste, the use of plasma energy has also been recommended.⁵⁴ Organic Rankine cycle combined with the MSW incinerator has also been used to process cleaned SMW.¹⁰¹

The goal programming (a program that is commonly used to optimize a process) was used to determine the most suitable incineration location of SMW in Serbia to minimize environmental pollution and risks.^{109,110} The optimization models are also noted to be useful for the hospital waste management decision-making process.¹¹¹ The application of root cause analysis, risk matrix, failure mode effects analysis, event tree analysis, hazards and operability study, etc. has also been reported in optimizing SMW management systems.¹¹⁰ Compositional Bayesian regression has also been applied to predict waste generation and its environmental impacts.⁷² The system approach¹¹² and the neural network modeling^{88,113} have also been used in MSW management processes.

Countries have twisted/turned away from landfilling to incineration due to environmental concerns and the scarcity of landfilling area¹¹⁴ and to mitigating global waste management problems,⁸⁰ which should be widely adopted with technological advances and greater investment in the waste management sector. Incineration reduces 80–95% of the volume of solid waste;^{115,116} thus, this would be the better option during the pandemic in controlling infectious diseases and mitigating environmental pollution; however, the risk of spreading infectious diseases during transportation remains.¹¹⁷ The mobile incineration process with heat and energy recovery would be a potential solution to reduce risks during transportation. However, the composition of MSW may have played an essential role in selecting waste management technologies. In developing countries, organic waste is the main contributor to the MSW; however, paper and plastics have dominated in the developed countries.^{72,80,106}

The double chamber incinerator reduces emissions by increasing gas residence time and encouraging turbulence in the chamber.⁵⁵ The incinerators equipped with the fluidized bed or moveable grate technology are commonly used to manage MSW, but the fluidized bed incinerator is losing ground because of the requirement of energy-intensive pretreatment (such as shredding) and higher fly ash generation.⁷⁹ On the other hand, movable grate incinerators can be used to manage the waste as received, which might be useful in processing COVID-19 waste and mitigating particulate emission. In Australia, Brazil, and in Asia (except China), only the movable grate incinerators are used to manage MSW. However, in other regions or countries, the use of fluidized bed and rotary kiln technology were 20–29 and 3–8%, respectively (Figure 5).⁸⁰

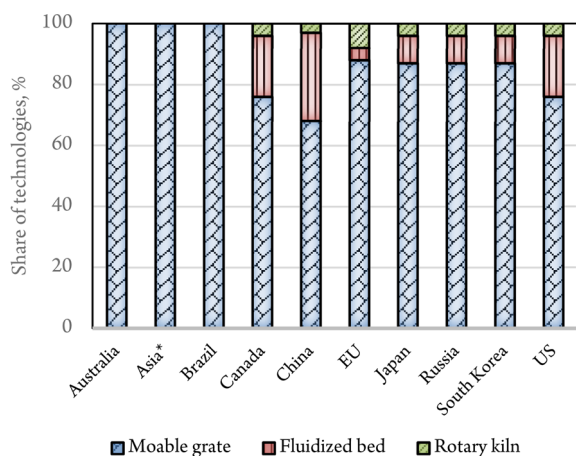


Figure 5. MSW incineration technologies used in different countries/regions (*except China). Reproduced from ref 80 with permission, Copyright 2018 Elsevier.

The waste management associations in the EU were urged to make the circular economy action plan and European green deal as an integral part for the COVID-19 recovery plan as well as call for discussion for proper management of residual waste.¹¹⁸ The WHO recommends three categories of contaminated waste management technologies based on their preference. For example, open burning or burning in pit is identified to be the least preferable, whereas autoclaving, single and double chamber incinerators are intermittent, and dual chamber incineration as well as the low heat-based chemical processes are the most preferable technologies (Figure 6).¹¹⁹ Waste segregation and separate treatment of waste streams depending on their characteristics is found to be the key to reducing the environmental impacts of the waste management system. For example, anaerobic digestion of food waste, recycling of the recyclable portion of MSW instead of

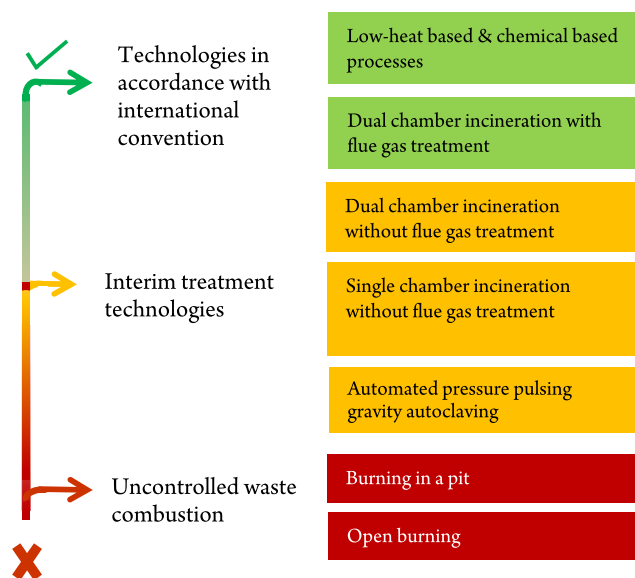


Figure 6. Recommended technology ladder for contaminated healthcare waste. Reproduced from ref 119. Copyright World Health Organization, License CC BY-NC-SA 3.0 IGO (<https://creativecommons.org/licenses/by-nc-sa/3.0/igo/>).

incineration, as well as waste prevention are noted to be environmentally beneficial.¹⁰⁸

DISCUSSION

The pandemic outbreaks have a significant effect on the generation of MSW and SMW as well as their management. Although waste collection has a vital role in recycling and recovery, disrupted waste collection and management have created numerous problems in waste management systems such as recycling activities, thus in the circular economy.¹²⁰ The governmental directives on COVID-19 failed to mitigate the hassles of waste collectors/workers.^{36,121} Some of the collectors face health problems probably from infectious diseases because of the presence of disposed face masks, hand gloves, and other contaminated medical waste in the waste stream collected.¹²¹ Consequently, waste workers have advocated for more equitable and inclusive urban policies, especially during COVID-19.¹²²

Inadequate waste management during the pandemic and postpandemic period aggravates waste management and intensifies infectious disease transmission. Technological advances (design, decentralization, automation, etc.) and investment by both public and private institutions can enhance uninterrupted waste collection and management. Although the mobile incineration process might be a suitable option in the timely management of infectious waste, it may raise air pollution in a populated area, as the healthcare facilities are usually located in urban and populated areas that need to be carefully addressed.

Solid waste management data play a vital role in waste management planning and policy development, especially with the increasing population growth and urbanization.⁴ A database on the waste generation and waste management in prepandemic and pandemic periods will be useful in predicting waste generation and preparing for an effective waste management for any future pandemic outbreak. In addition, any attempt in easing regulations and rules on contaminated waste management has to be done with careful consideration.

It has also been estimated that various measures imposed to control the spread of COVID-19 emerged to be beneficial to the environment but has a reverse impact on the economy. For example, in New York, air pollution dropped to 50% compared to last year; however, China observed a 25% decrease in emissions.²² Due to the mixed impact of the COVID-19 pandemic and prediction of long-term economic, behavioral, and societal changes,¹²³ system dynamics and causal loop diagram modeling could help for better understanding of the changes in the waste generation.^{39,112}

Although various waste management systems have been implemented due to the pandemic, their environmental, economic, and societal impacts/viability need to be evaluated. The initiative to improve the sustainability of waste management systems by increasing the recycling rate may be disturbed because of the pandemic as countries/regions are forced to adjust their waste management strategies to control the spread of infection. Consequently, adequate/appropriate disinfection coupled with incineration would be a recommended waste management system during this pandemic to improve the sustainability of the waste management system.

SUMMARY AND RECOMMENDATION

Segregation of contaminated and noncontaminated waste at the source and subsequent application of recycling and appropriate waste management strategies are recommended for mitigating the environmental impact of MSW and SMW during a pandemic scenario. This strategy needs to be continued even at the postpandemic period to reduce the environmental impacts and health risks. Numerous efforts are underway to minimize the waste management problems associated with an increased volume of MSW and SMW experienced by many jurisdictions during the COVID-19 pandemic. Although various programs are being implemented to improve the waste management systems during the pandemic, innovative methods are required to safely handle the infectious waste while minimizing environmental impact, ensuring sustainable waste management and overall contributing to a circular economy. Technological advances are a must for minimizing waste management problems, and the inclusion of stakeholders from every sector of the waste management systems would be key in developing sustainable waste management policies. This can ensure that waste management systems are resilient in the event of future crises.

In addition, careful consideration needs to be placed in technological choice depending on the waste composition, locations, and social acceptance. To improve the sustainability of waste management systems, the following initiatives can play an important role:

- Design and development of alternatives to conventional single-use plastics including PPE.
- Initiate an integrated waste management by engaging the stakeholders associated with MSW and SMW.
- Finally, a broader sustainability check is imperative to determine the systems economic and environmental viability that can mitigate the risk on investment thus in improving the waste management system's sustainability.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acsenvironau.1c00005>.

Information on the emission limits and composition of waste streams (MSW) in different regions/countries ([PDF](#))

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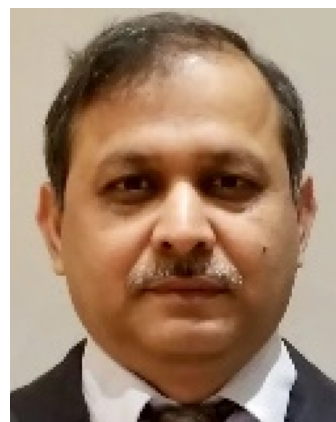
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Notes

The authors declare no competing financial interest.

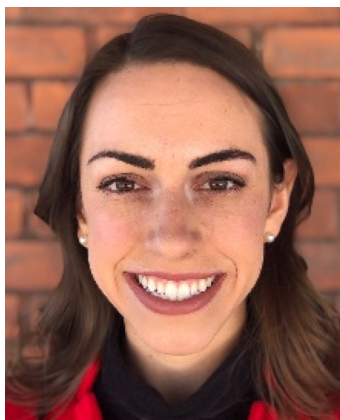
Biographies



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