

Repercussions of COVID-19 pandemic on solid waste generation and management strategies

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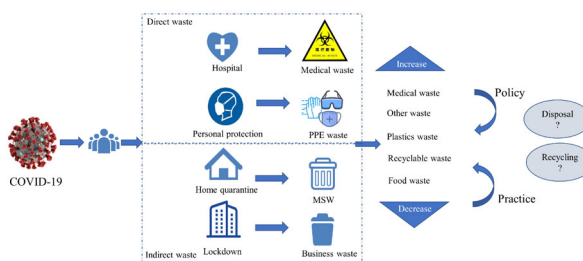
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HIGHLIGHTS

- Implication of COVID-19 on medical waste and MSW generation is studied.
- Challenges and effective strategy of solid waste generation is reviewed.
- 2.9 million tons of COVID-19 related medical waste has been generated until Sep. 22.
- The pandemic has postponed policies related to the reduction of plastic use.
- Blockade resulted in a significant drop in waste generation in some regions.

GRAPHIC ABSTRACT



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ABSTRACT

It has been over ten months since the beginning of the 2019 coronavirus disease (COVID-2019), and its impact on solid waste management, especially medical waste, is becoming clearer. This study systematically reviews the potential influences of the COVID-19 pandemic on medical waste, personal protection equipment waste and municipal solid waste (MSW), and discusses the corresponding measures and policies of solid waste management in typical countries. The results show that the generation of medical waste from the pandemic increased significantly, with 18%–425% growth. It is estimated that the daily output of COVID-19 medical waste increased from 200 t/d on Feb. 22 to over 29000 t/d at the end of September 2020 throughout the world. The use of personal protective equipment will continue to grow in the long-term, while the blockade and isolation measures greatly reduced the volume of commercial waste, especially for tourist cities, and part of this waste was transferred to household waste. Residents' attitudes and behavior toward food waste have changed due to the COVID-19 pandemic. In response to the pandemic, international organizations and several countries have issued new policies and guidelines and adjusted their management strategies for medical waste and MSW treatment. The pandemic has brought specific challenges to the disposal capacity of medical waste worldwide. It has also brought about the stagnation of policies related to the reduction of plastic products and waste recycling. This study will provide some useful information for managers and governmental officials on effective solid waste management during and after the COVID-19 pandemic.

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1 Introduction

The 2019 coronavirus disease (COVID-19) which has been classified as a pandemic by the World Health Organization (WHO) (WHO, 2020a) has changed the

world greatly since it was first reported in early December 2019. As of 22 September 2020, it had spread to more than 215 countries and regions; over 31 million people have been diagnosed with COVID-19 all over the world (23 million have recovered) (Worldometer, 2020); and the amount of confirmed cases is still climbing. Most countries/regions have implemented complete to partial lockdowns, including home quarantines and curfews, restricted/banned international and domestic travel, prohibited public gatherings, and declared emergency status to combat COVID-19 (Lal et al., 2020).

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Besides the negative impacts on global economic activities, the response to the pandemic of COVID-19 has brought several positive environmental changes in some areas, such as the reduction of CO₂ and NO₂ emissions and the improvement of water quality (Eroglu, 2020; Espejo et al., 2020). However, the impacts of COVID-19 on solid waste generation and management are not inspiring. With the rapid rise in the number of confirmed cases, many types of COVID-19-related waste from hospitals, healthcare facilities, and individuals, including infected masks, gloves, and other protective equipment, are being generated during the pandemic. COVID-19 has had a significant impact on the generation of not only medical and health care waste but also of municipal solid waste (MSW) production and composition. These wastes can be divided into two types: COVID-19-related waste and indirect waste (such as non-medical MSW). According to the WHO and the US CDC, COVID-19-related waste can also be classified as two kinds. One is waste within hospitals and health-care facilities: all waste generated within treatment facilities should be considered medical waste and should be collected and disposed of with additional precautions and care. Another is waste outside those facilities. This includes waste from social distancing and other preventive measures (e.g., masks, gloves) (Somani et al., 2020). This last kind of waste can be treated as harmless waste.

The pneumonia outbreak of COVID-19 has greatly increased medical waste generation and the use of personal protective equipment (PPE). COVID-19 waste in the US is estimated increase from 5 million tons/year to 2.5 million tons/month (Ilyas et al., 2020), and from the pandemic outbreak to the end of April, South Korea generated 1960 tons of medical waste with the daily generated medical waste increasing from less than 10 t to a peak of 50 t (ESCAP, 2020). There has been a large increase in the amount of single-use plastics (including PPE) (Basel Convention, 2020a; UNEP, 2020a). Single-use plastics, also referred to as disposable plastics, are items intended to be used only once before they are thrown away or recycled, e.g., grocery bags, food packaging, bottles, etc. (UNEP, 2018). The demand for PPE (facemasks and surgical gloves) is not expected to decline during the post-pandemic period, but is estimated to increase 20% up to 2025 (WHO, 2020b).

The pandemic has altered the waste generation dynamics (Ragazzi et al., 2020), with potential criticality in the waste management at the collection and treatment stages (Peng et al., 2020). Ironically, the spread of COVID-19 may be increased by inadequate waste management (WHO, 2020c). Ensuring that related solid waste is collected and disposed of in a timely and orderly manner, as well as harmlessly and efficiently, has also become an important part of the battle against the pandemic (SCIO, 2020). Effective management of medical waste requires appropriate identification, collection, separation, storage, trans-

portation, treatment, and disposal, as well as important associated aspects including disinfection, personnel protection, and training. The safe management of household waste is also likely to be critical during the COVID-19 emergency. PPE wastes such as contaminated masks and gloves should be stored separately from other household waste streams and collected by a municipal waste specialist or waste management operators.

Several studies have focused on the environmental impact of COVID-2019 (Table 1), analyzing the positive and negative effects on the environment including air and water quality, cleanliness of beaches and other public spaces, environmental noise level, plastic waste, medical waste, and MSW. Meanwhile, the systematic analysis with more specific information on medical waste generation, collection, treatment and management policies worldwide are still lacking. The effects on MSW and food waste generation are also unknown. This study illustrates the global challenges and proposes an effective strategy of solid waste management responding to the 2019–2020 novel coronavirus pandemic, referring to the implications of COVID-19 for solid waste generation (especially medical waste), management regulations or policies, and the responses and practices of different countries. The study also presents specific insights into the changes in the dynamics of plastic waste and food waste generation because of the pandemic, and the challenges to the current MSW management systems.

2 Implications of COVID-19 on waste generation

2.1 Medical waste

2.1.1 Changes in medical waste types and rates

Medical waste includes waste generated from biomedical research institutions, medical institutions, and medical laboratories, as well as waste from dispersed sources (Rupani et al., 2020). Although hospitals generate large amounts of medical waste, they represent a small proportion of the total sources of waste. In general, of the total amount of waste generated by health-care activities, about 75%–90% is general, non-hazardous waste, such as plastic, paper and office waste. This waste can be processed through regular procedures and does not require any special handling under normal conditions (WHO, 2018; UNEP, 2020b). However, during a pandemic, as suggested, all waste generated within treatment facilities should be considered as medical waste and should be collected and disposed of with additional precautions and care. The modification of existing waste treatment facilities to manage unusual medical waste requires adequate information on the amount of medical waste generated and the treatment facilities available (Sarkodie

Table 1 A review on the environmental effects of the COVID-2019 pandemic

Content of the study	Scope	References
Waste management, air quality improvements, waste incineration, wildlife, global migration, and sustainability.	Worldwide	Rupani et al., 2020
Ocean environment, air and water quality	Worldwide	Saadat et al., 2020
NO ₂ and PM _{2.5} , cleanliness of beaches, environmental noise level, waste generation, and waste recycling	Worldwide	Zambrano-Monserrate et al., 2020
Waste and wastewater	Worldwide	Nghiem et al., 2020
Implications of COVID-19 on plastic waste generation	Worldwide	Vanapalli et al., 2021
Plastic pollution due to COVID-19 pandemic	Worldwide	Patrício Silva et al., 2021
Plastic waste management	Worldwide	Patrício Silva et al., 2020
Medical waste administration	India	Ramteke and Sahu, 2020
Emergency response to health care wastes	China	Yang et al., 2021
Management of used personal protective equipment and wastes	South Korea	Rhee, 2020
Re-use and sustainable waste management of PPE	The Republic of Ireland	Rowan and Laffey, 2020
Food waste management	Spain	Aldaco et al., 2020
Consumer awareness, attitudes, and behaviors related to food wastage	Tunisia	Jribi et al., 2020
MSW management	Italy	Ragazzi et al., 2020
Covid-19 effects on MSW management	Brazil	Penteado and Castro, 2021
MSW management practices	Worldwide	Kulkarni and Anantharama, 2020
MSW from household, business, and industrial waste	Singapore, China, and Czech Republic	Fan et al., 2021
Medical waste, plastic waste, and food waste management	Worldwide	Sharma et al., 2020

and Owusu, 2020b).

The waste generated in healthcare facilities can vary from 0.04 to 5 kg/(patient·d). An evaluation of waste generation rate data from all over the world shows that medical waste from hospitals is about 0.5 kg per bed per day (UNEP, 2020c). There is no doubt that the pneumonia outbreak of COVID-19 has greatly increased the amount of medical waste, especially infectious medical waste, throughout the world. It is estimated that medical waste from healthcare facilities associated with COVID-19 is increasing by 3.4 kg/person/day (UNEP, 2020c). In Delhi, India, medical waste in administration or private emergency clinics has gone up from 0.5 kg to 2.5–4 kg per bed per day (Ramteke and Sahu, 2020). According to a case study by (Peng et al., 2020) in a Chinese hospital, the average daily output of COVID-19-related waste is more than 6 kg per bed per day (in a total of 24 COVID-19 patients with no deaths). At present, China produces medical waste mainly from nucleic acid detection, with an average of about 0.1 kg per capita, based on our field interviews.

2.1.2 Medical waste generation in typical countries and regions

As shown in Table 2 (MEE, 2020a; MHC, 2020), the rise in the cases of COVID-19 in a central city, China generated

nearly 247 t of medical waste per day at the peak of the pandemic, nearly four times more than before the pandemic. The peak occurred from Feb. 15 to Mar. 15. After that time, it gradually declined back to normal by mid-May. National collected medical waste increased from 2661 t on Feb. 11 to about 3600 t. The wastes generated from quarantine areas are officially quantified as medical wastes. Before the outbreak, the daily domestic garbage and medical waste generated by a hospital were stored separately; during the epidemic, all garbage should be treated as medical waste, including lunch boxes used by patients (Fu, 2020). Therefore, the average personal medical waste during this period increased greatly. In early March, the medical waste generated in the city increased to 5.8 kg/(patient·day) and to 11 kg/(patient·day) in China as a whole, based on the active cases. In fact, even the medical waste generated by suspended cases and testing takes up quite a large portion.

Other cities and countries have also suffered from the increase of medical waste generation—for example, South Korea, Spain, Iran and India (Table 3). The highest increase rate appeared in Spain; the Waste Agency of Catalonia detected a 350% increase in COVID-19 medical waste since mid-March. Since the start of the confinement in March, it has reached 1200–925 t higher than usual (ACR, 2020). Medical waste is generated in many different facilities. According to the South Korean Ministry of

Table 2 Medical waste generation in China

Date	The central city			China		
	Active cases	Total cases	Medical waste generation (t)	Collected medical waste (t)	COVID-19-related medical waste (t)	Accumulation from Jan 21(thousand tons)
2.11	–	19558	47	2661	489	–
2.24	34691	47071	201	2719	588	99
3.1	25903	49315	247	–	–	–
3.3	22368	49540	210	3136	570	123
3.14	9911	49999	210	3300	458	15.9
3.21	5143	50005	178	3475	380	182
3.28	2045	50006	173	3591	404	207
4.4	644	50008	109	3413	342	232
4.11	302	50008	122	3481	237	256
4.18	109	50333	99	3471	205	280
4.25	12	50333	68	3447	186	304
5.9	0	50334	55	3400	–	349
5.16	6	50339	54	3461	–	374
5.23	7	50340	65	3475	–	398
5.30	4	50340	–	3560	–	422
6.8	0	50340	–	3499	–	447

Table 3 Medical waste generation in some regions

City or Country	Medical waste generation	Cumulative cases in the research period	Source
South Korea	By mid-July, it increased to over 2600 t	27 cases on Feb. 10 to 13551 cases on Jul. 15.	MoE Korea, 2020
Catalonia, Spain	1200 t (350% increase), from mid-March to mid-April	6475 cases on Mar. 15 to 142915 cases on Apr. 15 (Spain)	ACR, 2020
Tehran, Iran	80–110 t per day during the pandemic (18%–62% increase)	54 cases on Mar. 1 to 2750 cases on Mar. 30 (Iran)	Zand and Heir, 2020
Ahmedabad, India	1000 kg/d (67%–82% increase). 3000 kg/d in the future	–	TOI, 2020

Environment (MoE), from early February 2020 to early March 2020, approximately 295 t of COVID-19 medical waste was generated from quarantine hospitals (180.6 t), temporary isolation facilities (61 t), isolated life treatment centers for patients (39 t) and community treatment centers (15 t) (MoE Korea, 2020). Based on the above information, it is calculated that the average medical waste generation during the pandemic has varied from 2.5 to 5.8 kg/(patient·day); 4 kg/(patient·day) has been chosen here, to estimate medical waste generation in different areas and dates in the following section.

2.1.3 Estimation of medical waste generation worldwide

Medical waste generation data are used to estimate the required capacity of the waste treatment facilities, and also to optimize the waste management systems and carry out

national assessments and planning. The waste generation rate in healthcare facilities is affected by several factors such as number of occupied beds, average length of stay of patients, location (rural or urban), procurement policies, temporal variations, and the country's level of development (Basel Convention, 2020b). To estimate the total medical waste generation related to COVID-19 around the world, a simplified method is used, and some assumptions are made here: 1) medical waste generation increased to 4 kg/(patient·day) during the COVID-19 pandemic; 2) the daily increase number of active cases in each month is fixed and the start date is Jun. 22; 3) The medical waste from routine nucleic acid detection is not included. The calculation for daily waste generation is shown in Eq. (1):

$$W_{\text{Daily}} = C \times w_{\text{Average}} \quad (1)$$

where W_{Daily} is the medical waste amount in a specific day,

C refers to number of active cases on that day, and $w_{Average}$ represents the average waste generation (4 kg/(patient · day)). The monthly cumulative generation is estimated by the sum of daily waste generation.

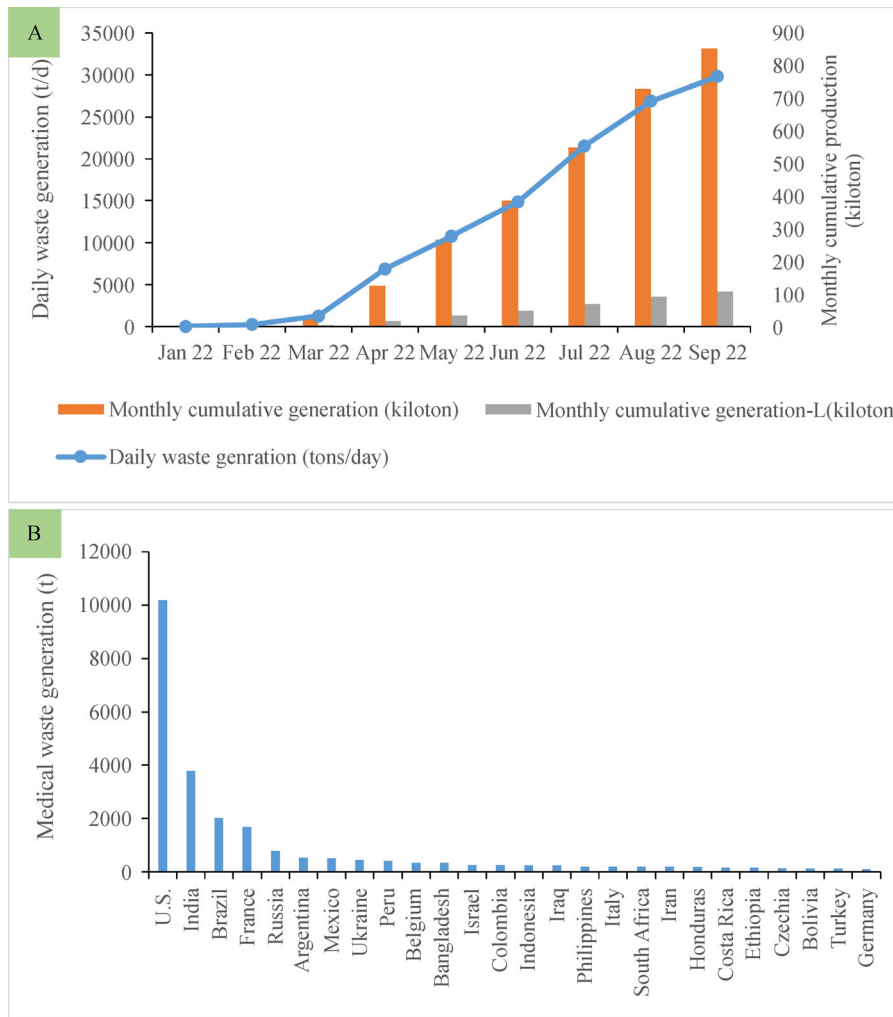
The estimation is shown in Fig. 1(A): 2 tons of COVID-19-related medical waste was generated on Jan. 22, and the data increased to about 29825 t on Sep 22. The monthly medical waste generation increased from 3391 tons to 852 000 tons. In total, 2.9 million tons of COVID-19-related medical waste has been generated during the last 8 months. Using a lower waste generation rate (0.5 kg/(patient · day), the average generation rate before the pandemic) the total amount is estimated as 0.4 million tons. Medical waste generated in different countries by the end of September is shown in Fig. 1(B); only countries generating over 100 tons/day are included. The US generated more than 10000 tons on Sep 30, far more

than other countries, and India, Brazil, and France generated 1690, 2009, and 3776 t, respectively.

2.2 PPE waste

PPE is considered the most reliable and affordable defense against infection and transmission of the virus. At the beginning of the pandemic, to prevent the spread of the virus, PPE—such as medical masks and gloves—was used mainly by healthcare professionals. But with the growing spread of the virus, those PPE items have become mandatory for the entire population in many countries.

Millions of PPE are being manufactured and used daily by ordinary citizens during the pandemic (Table 4). For example, the Republic of Ireland is a small country with a population of about 4.5 million, but its health workers use up 9 million masks a week (Farsaci, 2020). However, the



* Monthly cumulative generation—L means the daily waste generation is 0.5 kg/patient

Fig. 1 Estimation of COVID-19-related medical waste generation around the world. A. Medical waste generation on different dates; B. Medical waste generation in different countries on Sep 30, 2020 (any country with daily medical waste over 100 t).

Table 4 Estimation of number of masks used in some studies

Region	Estimated data	Condition	Reference
The Republic of Ireland	9 million masks/week	Used by health workers	Farsaci, 2020
Africa	700 million masks/day	80% acceptance rate and an average of 2 face masks daily per capita	Nzediegwu and Chang, 2020
Tehran, Iran	5.5 million masks/day	32% of the residents of Tehran agreed to use PPE	Zand and Heir, 2020
Italy	40 million masks/day	Two-thirds of the whole population are wearing masks	Ragazzi et al., 2020

use of PPE by ordinary citizens also makes up a major part of the total. More than 50 countries/territories have mandated compulsory facemask use for their citizens (Sarkodie and Owusu, 2020b). Italy would normally dispose of about 40 million masks daily, with a total amount of about 44,000 tons. This amount is 0.14% of the national total MSW, and when 40 million pairs of single-use gloves are included, the ratio of PPE used by citizens would increase to 0.59% (Ragazzi et al., 2020). Based on these data, the impact of millions of PPE seems to be not much, considering MSW management at the national level alone. But because this PPE, along with its possible residual viruses, is easily blown away into open water by the wind, their management cannot be ignored.

A mask is mainly composed of plastic (>80%) (Prata et al., 2020), and thus the increased demand for single-use PPE by healthcare professionals and the mandated use of masks for the public have transformed the dynamics of plastic waste generation. Indirectly, the COVID-19 pandemic has enhanced the complexities of plastic waste management and seems to hamper the efforts to reduce plastic pollution (Vanapalli et al., 2021; Sarkodie and Owusu, 2020b).

2.3 MSW generation

2.3.1 Plastic waste

The concerns about the survival of the virus have changed our behavioral patterns. Along with lifestyle changes that increase plastic use for convenience and reassurance, consumers have shifted from worrying about plastic waste's environmental impacts to preferring plastic packaging for hygiene and health reasons, during the pandemic (Grodzińska-Jurczak et al., 2020).

In the beginning, the sudden lock-in and fear of the virus led to a surge in disposable products and panic purchases (Sarkodie and Owusu, 2020a). Demand rose sharply for packaging for groceries, healthcare products, and e-commerce transportation (Feber David 2020). The demand for consumer-packaged goods grew by 9.5% in the United States, which may be attributable to consumers stockpiling food (Statista, 2020).

The quarantine policies established in most countries/regions have also caused consumers to increase their

demand for online shopping and food delivery services (Rupani et al., 2020; Rhee, 2020; Vanapalli et al., 2021). Compared to the reference period in January and February 2020, the online trading across 20 different industries increased in June, and even though it decreased on September 6, online transactions still increased (16.6%) compared to the index period (Clement J., 2020). According to the Korea Statistics Bureau, online shopping for household goods and food delivery services increased by approximately 20% (Statistics Korea, 2020). All these changes in consumption habits have increased the amount of plastic waste generation.

2.3.2 Food waste generation

COVID-19 has exerted a certain influence on food loss and waste (FLW) because of the consumption habits and food production changes it has caused. In a survey of US households ($n = 1005$) in April 2020 (Hunter, 2020), it was found that the number of households cooking at home was 54% more than before COVID-19, which may imply more food waste, but 57% also reported that they were wasting less food, which suggests that the net effect could amount to no or little change in the organic waste stream.

During an uncertain situation such as the COVID-19 pandemic, individuals with higher cognitive closure (NFC) waste more food compared with people with low NFC. This effect is caused by the feeling that there is a shortage of food, resulting in unnecessary food purchases (Brizi and Biraglia, 2021). Consumption data in Spain shows that food purchases increased in the first two weeks of the lockdown (29.8% and 10.9% increases), then decreased 20.3% in the third week. The COVID-19 outbreak had a slight influence on the total amount of FLW in Spain: FLW generation in households increased by 12% (Aldaco et al., 2020). But if it is true that non-household consumption was absorbed by households during the outbreak, the overall amount of FLW generated is still similar to that in 2019.

The COVID-19 lockdowns have also an impact on consumers' awareness, attitudes and behaviors. In an online survey in Tunisia, 85% of the respondents said that they would not discard what they bought, and 93% of the respondents wanted to try to control their food waste levels during the COVID-19 lockdown. The prevention of food

waste may, however, be due more to the socio-economic context of the COVID-19 crisis (i.e., food supply, limited mobility, loss of income) than to environmental concerns (Jribi et al., 2020).

2.3.3 MSW generation data

The announcement of the lockdowns and travel restrictions resulted in a significant drop in waste generation in some regions (Table 5), especially tourist cities. Due to the high concentration of labor, commercial and tourist activities in cities that are now closed or have reduced activity, waste generation in Barcelona fell by 25%. MSW generation in Macao, a typical tourist city in China, decreased 17%–25% between February and May. In Milan, Italy, the strict blockade system resulted in a 28% reduction in total waste production in 10–14 weeks, 2020, including a 24% reduction in residual waste, household food waste reduction of 14%, and commercial food waste reduction of over 80%.

Another reason for the decline in waste generation is the reduction of recycling activities: citizens accumulate some MSW at home rather than at collection centers. In India, recycling activities have been stopped, and the amount of MSW reaching landfills/junkyards decreased by 20%–40% (Somani et al., 2020). MSW generation in Catalonia, Spain has fallen to about 17% lower than in a normal month.

On the other hand, the pandemic has increased waste generation in other areas. In England, a survey of local governments in late May 2020 found that more than 90% of local authorities reported higher waste generation and waste collection than usual, and 58% reported increases to be in the range of 0%–20% greater than normal (ADEPT,

2020). The social distancing measures of COVID-19 led to the closure of businesses and schools, reducing waste generation, but transferred part of the waste to households (Naughton, 2020). In Tokyo, Japan, the commercial waste amount decreased by 57% in May, 2020, while the household waste amount increased by 110%.

3 Response to waste management and treatment systems

The regions with high COVID-19 incidence rates are struggling to manage the dramatic increase in the amount of medical waste generated in the treatment, personal protection and testing processes (Klemeš et al., 2020). However, many developing countries were already facing poor management of medical waste before the COVID-19 pandemic (Rahman et al., 2020). In some countries, medical wastes along with MSW are dumped in the open or in poorly managed landfills (Nzediegwu and Chang, 2020). In addition, open burning and incineration without proper pollution control expose waste workers and surrounding communities to toxic pollutants from air emissions and ash. In India, the net generation of medical waste is 405 tons/day, of which just 292 tons/day is disposed of, implying that practically 28% of the wastes are left untreated (Ramteke and Sahu, 2020). According to the Asian Development Bank, these cities like Manila, Kuala Lumpur, Hanoi, and Bangkok would produce 154–280 tons/day of medical waste, and few cities have the capacity to deal with these expected excessive amounts of waste (ADB, 2020). To deal with the huge increase in medical waste generation, it is crucial to update

Table 5 MSW generation in different regions

Country or city	Generation	Source
Macao, China	From February to May, the MSW generation decreased by 17%–25%, compared to 2019	Environmental Protection Bureau (DSPA) Macao SAR, 2020
Khenifra and Tighassaline, Morocco	February and March 2020, compared to the same period of 2019, the MSW generation has decreased 2%–10%	Ouhssine O, 2020
Catalonia, Spain	MSW generation has fallen to an estimated 242000 t, 17%	Generalitat de Catalunya, 2020
Milan, Italy	27.5% reduction in total waste production	AMSA, 2020
Trento, Italy	4058 t, 14% lower than March 2019	Ragazzi et al., 2020
India	The amount of MSW reaching landfills/junkyards decreased by about 20%–40%	Somani et al., 2020
New York, US	Residential solid waste generation increased from 5 to 30% Commercial and industrial sector waste decreased by as much as 50%	WasteAdvantage, 2020
Tokyo, Japan	After Japan declared a state of emergency on 7 April 2020, the commercial waste amount decreased by 57% in May The household waste amount increased by 110% in May	UNEP, 2020c
England	May 2020, 58% reported increases to be in the range of 0%–20% greater than normal	ADEPT, 2020
Tehran, Iran	Landfilling of wastes in Tehran has increased by 34.7%	Zand and Heir, 2020

management strategies and rapidly increase the disposal capacity.

3.1 Policies and practices regarding medical waste during the COVID-19 pandemic

3.1.1 International guidelines

Waste generated during the pandemic has raised concerns regarding the potential role of waste residues in spreading the infection (Ragazzi et al., 2020). Some international organizations, such as the WHO, the Basel Convention, European Centre for Disease Prevention and Control (ECDC), and the United Nations Environment Programme (UNEP), have published the guidelines or reports on the correct management of medical waste and waste produced in households (Table 6) (Basel Convention, 2020c; ECDC,

2020; European Commission, 2020; ISWA, 2020; UNEP, 2020c; UNICEF, 2020a; 2020b)

The Basel Convention's guidance document—*Fact-sheet on Environmentally Sound Management of Medical Waste*—provides the information on how to manage medical waste in the most sustainable manner. This fact sheet is primarily intended for the use by waste managers at facilities generating or disposing of medical waste, but it also contains useful information for transporters and collectors. The WHO has provided information on hygiene practices, along with guidance on how to safely manage manure and wastewater, maintain the quality of the water supply, and manage medical care and household waste generated by quarantined personnel (UNICEF, 2020a; 2020b). *Waste Management during the COVID-19 Pandemic: from response to recovery* reviews current management practices for the waste from healthcare facilities,

Table 6 The responding policies and guidance plans to the COVID-19 pandemic

Guidelines and policies	Institution or country	Main content
<ul style="list-style-type: none"> • Water, sanitation, hygiene, and waste management for the COVID-19 virus: interim guidance • Water, sanitation, hygiene and waste management for COVID-19: technical brief 	WHO	WHO's guidance on virus-related water supply, sanitation, personal hygiene, and waste management for various types of viruses, including coronavirus.
<ul style="list-style-type: none"> • Waste Management during the COVID-19 Pandemic: from response to recovery. 	UNEP	Practical information, suggestions, and guidelines on Medical Waste Management and Municipal Solid Waste Management
<ul style="list-style-type: none"> • Factsheet on Environmentally Sound Management of Medical Waste 	Basel Convention	Supports the implementation of the environmentally sound management of hazardous wastes and other wastes.
<ul style="list-style-type: none"> • Waste Management During the COVID-19 Pandemic 	ISWA	Recommendations on three priorities for waste management
<ul style="list-style-type: none"> • Infection prevention and control in the household management of people with suspected or confirmed coronavirus disease (COVID-19) 	ECDC	Management of household waste
<ul style="list-style-type: none"> • Waste management in the context of the coronavirus crisis 	EC	Provides guidance on preventing and reducing disruptions in the provision of proper waste management services.
<ul style="list-style-type: none"> • Guide on Management and Techniques of Emergency Treatment and Disposal of Medical Waste Caused by COVID-19 (Trial). • Notice on the Management of Medical Waste in Medical Institutions for COVID-19 • Work Plan for Comprehensive Waste Management in Medical Institutions 	China	Management and technical guidelines on emergency treatment of medical waste for institutions
<ul style="list-style-type: none"> • Coronavirus (COVID-19): disposing of waste • COVID-19 waste management standard operating procedure • Cleansing and PPE waste at a healthcare waste management facility: RPS C1 • PPE waste from home healthcare workers treating patients with COVID-19: RPS C5 	UK	Waste management approach for all healthcare facilities; How to dispose of personal or business waste, including face coverings and PPE
<ul style="list-style-type: none"> • Extraordinary measures for Safety Management of Wastes Related to COVID-19 • Guidelines for waste treatment in residential treatment centers 	South Korea	Provides detailed management processes for medical waste from different sources
<ul style="list-style-type: none"> • Guidelines for Handling, Treatment, and Disposal of Waste Generated during Treatment/Diagnosis/Quarantine of COVID-19 Patients 	India	Provides guidance on segregation of general solid waste and biomedical waste and recommend on disposal of PPEs
<ul style="list-style-type: none"> • Guidelines for the novel coronavirus infectious wastes 	Japan	Types and characteristics of COVID-19 waste; messages when dealing with medical waste

households, and quarantine locations (UNEP, 2020c). A series of *COVID-19 Waste Management Factsheets* were published by the UNEP, to give instructions on aspects such as national medical waste capacity assessment and how to choose the best COVID-19 waste management technology (UNEP, 2020a).

3.1.2 Typical medical waste management policies and processes

Some governments have existing national legislation addressing healthcare/medical waste. Also, many countries immediately issued some new policies, guidance, and plans to respond to the COVID-19 pandemic (Table 6) (BCRC China, 2020; MoE Japan, 2020; GOV.UK, 2020a). Countries like China, and South Korea, have carried out the effective and successful measures for COVID-19 medical waste management. The lessons and successful measures that China gained from COVID-19 medical waste management could provide valuable information for many developing countries coping with a sudden increase in medical waste.

3.1.2.1 China

In response to the COVID-19 epidemic, China central government issued *Guide on Management and Techniques for Emergency Treatment and Disposal of Medical Waste Caused by COVID-19 (Trial)* (MEE, 2020b) and *Notice on Environmental Management of Medical Waste Caused by COVID-19* (NHC, 2020). They provide guidance to dispose of the COVID-19 medical waste in a timely and orderly manner, as well as harmlessly and efficiently, and to standardize the management and technical requirements. Even, some provinces also issued special COVID-19 waste management guidelines.

Waste from infected patients or suspected cases should be managed according to the Fig. 2. Medical waste

classification is the first step in hospital waste management. Medical waste and domestic waste generated by fever clinics, observation wards, isolation wards, and nucleic acid testing laboratories should be treated as COVID-19-related medical waste (Peng et al., 2020). Medical and health institutions with adequate facilities can store infectious medical waste separately. The storage place should be disinfected, and the temporary storage time should not exceed 24 h. To carry out the disposal of medical waste caused by pneumonia, facilities, the sufficient preparation in health and epidemic prevention must have been done, based on the requirements specified by health authorities.

3.1.2.2 South Korea

In the early stages of the epidemic, South Korea was one of the countries with the highest number of infected cases, ranking in the top five. Since March 2020, the number of cases nationwide has dropped significantly. Since the first infected case was confirmed on Jan 20 in South Korea, the MoE announced the first version of *Extraordinary measures for Safety Management of Wastes Related to COVID-19* on Jan 28 (Ilyas et al., 2020).

According to the new guidelines (MOHW, 2020), COVID-19-related waste cannot be stored more than 24 h and should be incinerated on the day of collection. The storage time and incineration time were both cut down compared with those in the earlier act, in which the maximum storage time was 7 days and the waste only needed to be incinerated within 2 days of delivery. Figure 3 presents the detailed management processes for medical waste. Waste from hospitals and residential treatment centers is to be treated as separate medical waste and controlled with the strictest measures. Waste management during self-quarantine varies according to the infection situation and the period of patient illness. Under the

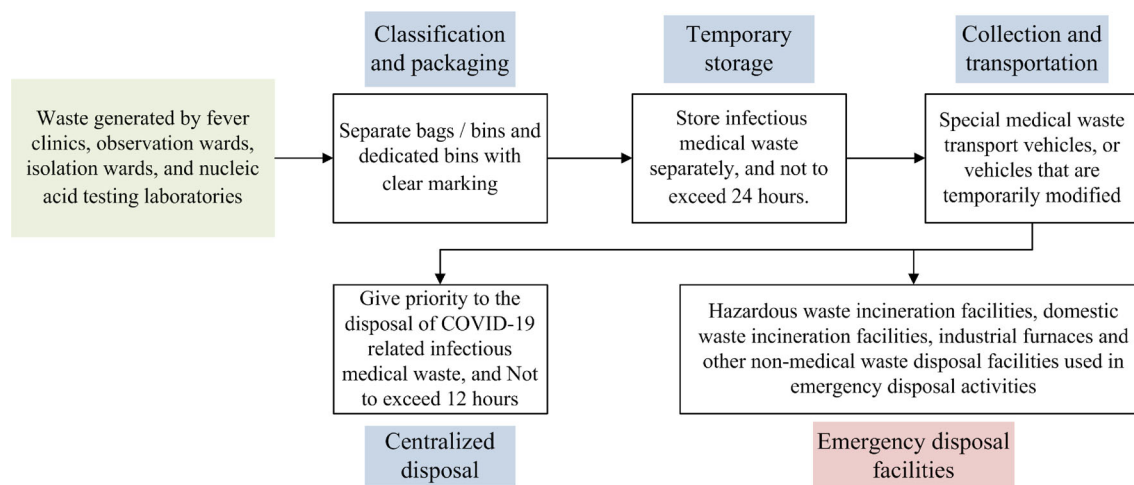


Fig. 2 Emergency disposal process and technical points in China.

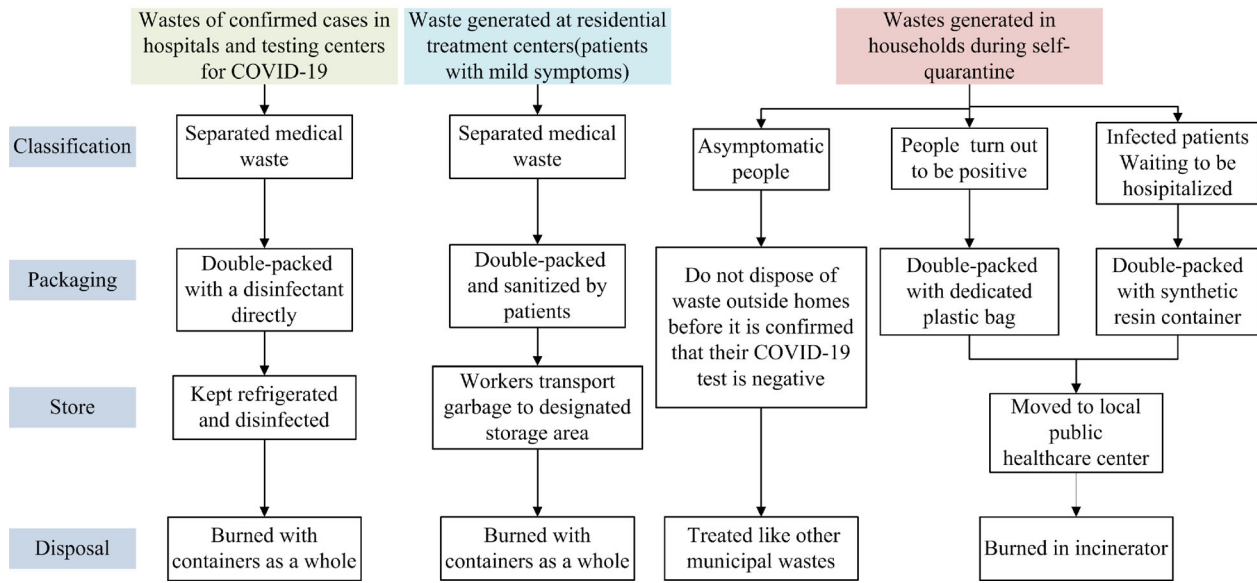


Fig. 3 Medical waste management system in South Korea (extract and organize from ESCAP, 2020).

extraordinary measures, the household waste from self-quarantined persons should also be treated as COVID waste (ESCAP, 2020).

3.1.2.3 Medical waste treatment processes in other countries

Currently, India has limited facilities for dealing with medical waste. Responding to the sudden increase in medical waste is a huge challenge for local authorities. On March 18, 2020 the Central Pollution Control Board, New Delhi released a set of guidelines on dealing with the waste from diagnosis, treatment, and isolation of COVID-19 patients (Ramteke and Sahu, 2020). In this case, the isolation ward of the hospital needs to maintain independent light-shielded coded tanks to isolate the waste. A special container labeled “New Coronary Pneumonia” should be placed in a different, temporary additional space and access to it should be controlled.

In Iran, due to the COVID-19 pandemic, the disposal of infectious waste in hospitals has completely stopped. Although the medical waste in Tehran is supposed to be divided into four categories—non-hazardous waste, medicines/chemicals, infectious waste, and sharp waste, only 47.3% hospitals are satisfactorily following these guidelines. Currently, hospital waste is collected in double or triple bag bags and transported to the Aradkouh treatment site, where it is buried in designated ditches (compacted waste sprayed with hydrated lime) (Zand and Heir, 2020).

In Romania, the National Institute of Public Health announced that household waste generated in quarantine sites is infectious waste (March 18, 2020), and strict waste management procedures must be implemented. These

wastes must be collected by specialized waste operators and transported, at -4°C , to hazardous waste incinerators (Mihai, 2020).

Information from the CDC, US shows that medical waste from healthcare facilities treating COVID-19 patients is no different from other medical waste and should be processed following routine procedures. Medical waste and infectious waste are subject to state solid waste regulatory programs (CDC, 2020; TCEQ, 2020).

Comparing the management policies and treatment processes in different countries, taking China and Korea as examples, it can be seen that besides the basic classified collection, double packaging, storage, and disposal, there are some differences because of local situations. In Korea, different collection and disposal processes are adopted depending on the source of the medical waste, such as from hospitals, residential treatment centers and self-quarantined households, while in China there are stricter requirements on the disposal time, which is not to exceed 12 h. China also gives clear guidance for emergency treatment priorities, diversion mode and treatment facilities. Differences also exist in the disposal technologies, as will be discussed in the following section.

3.1.3 Disinfection and disposal technologies

Different disinfection and disposal methods should be adopted based on various factors such as the quantity and type of waste, and the disposal and maintenance costs. A comprehensive introduction of disinfection and disposal technology is shown in Table 7 (Ilyas et al., 2020; Wang et al., 2020). The common incineration technologies include pyrolysis vaporization incinerators, rotary kiln incinerators, plasma incineration technology, etc. In

Table 7 Disinfection techniques for medical wastes

Technologies	Specific technologies	Characteristics	Waste volume	Costs	Maintenance
Chemical disinfection	Sodium hypochlorite, calcium hypochlorite, chlorine dioxide	Broad sterilization spectrum, rapid and stable performance; Residual disinfectants after disinfection.	< 10 t/d	Low	Easy
Physical disinfection	Microwave disinfection	Low action temperature, energy-saving, slow heat loss, and less pollutant release without gaseous emissions; relatively narrow disinfection spectrum and complex impact factors of disinfection.	< 10 t/d	High	Complex
	High-temperature steam disinfection	Available in various volumes, using heat released by water vapor to make pathogenic microorganisms undergo protein denaturation and coagulation; weak odor control.	< 10 t/d	Low	Easy
Incineration	Pyrolysis vaporization incinerator	The organic components of the waste are decomposed into flammable gases in order to avoid dust due to the turbulence caused by the excess air; high investment costs and strict requirements on heat levels of wastes, potential emission of carcinogens.	>10 t/d	High	Easy
	Rotary kiln incinerator	Enables the wastes to be well mixed, improves incineration efficiency; high dust content in the exhaust, high air volume requirements, high investment and maintenance costs, potential emission of carcinogens.			
	Plasma incineration	Transfers energy through plasma; wastes can be quickly decomposed into small molecules and even atoms. High requirement for technical personnel and high costs, potential emission of carcinogens.			

general, a combination of chemical disinfection and incineration should be adopted. The waste treated by physical disinfection can end in a municipal landfill. However, some countries require the waste to be rendered unrecognizable. Specific treatments are still needed depending on local legal regulations (Basel Convention, 2020b). Incineration is one of the most widely used technologies, as it is safe, simple, and effective (Wang et al., 2020).

In addition to the choice of disinfection and disposal technologies, another question is whether to use on-site, mobile, or off-site treatment. If the existing systems for medical waste treatment are overloaded, industrial furnaces and cement kilns could be appropriated for use (ADB, 2020). In China, on-site and mobile treatments are considered to be preferable due to their flexibility in responding to shifting demands. There have always been advantages and drawbacks to all ways, and the policies are also subject to context-specific constraints (Klemeš et al., 2020).

The medical waste generation in a central city, China far exceeded the existing treatment capabilities soon after the pandemic began. Fixed facilities, mobile facilities, co-processing facilities (MSW incineration plants), and non-local disposal were all successively used. Mobile facilities and non-local disposal (2.6% of waste was sent to nearby cities for harmless disposal) are auxiliary means (Yang et al., 2021). Mobile incinerators can be used to dispose of

discarded PPE such as face masks, gloves, and other contaminated single-use protective gear (Chen and Guo, 2020). The waste disposal capacity has now achieved 280 t/d, while before the COVID-19 outbreak, the medical waste disposal capacity is about 50 t/d. These practices can provide the reference models for other densely populated metropolises.

3.2 MSW management adjustments

The survival time of coronaviruses on the surfaces of metal, glass, and plastic surfaces is in the order of days (up to 9 d) (Kampf et al., 2020a, 2020b), indicating that the waste from households with positive or suspected COVID-19 patients may contain viable SARS-CoV-2 and could be a source of infection for some time (Nghiem et al., 2020). Waste collection and handling may pose a risk to MSW operators if they are exposed to waste contaminated by infected individuals (Ragazzi et al., 2020). In this section, the different responses to MSW management are summarized. PPE waste, as the most representative waste, is discussed separately.

3.2.1 PPE waste management

In South Korea, the used masks from a household can be placed in a regular garbage bag under the volume-based waste fee (VBWF) program. Waste containing used masks

must be incinerated or landfilled; no recycling is allowed (Rhee, 2020). In the UK, if the residents belong to the self-isolating people, their masks or PPE waste should be put into a double bag and stored for 72 h before putting them in a 'black bag' waste bin; otherwise, the masks and PPE are disposed of in a 'black bag' waste bin without extra bags or special storage. Businesses or other organizations, however, do not need to collect PPE separately (GOV.UK, 2020b). The Portuguese Environment Agency recommends that all PPE waste from ordinary citizens should be treated as mixed waste (rather than recyclables), placed in sealed and leak-proof garbage bags, and may then enter incineration facilities (preferably) or landfilled daily (Patrício Silva et al., 2021).

China has not issued any national guidelines on the management of PPE waste. Instead, some provinces have published a local technical guide for PPE waste management. For example, in Sichuan province, the used masks should be collected and disinfected before the incineration. In Guangdong, on the other hand, for ordinary people, their masks can be directly thrown into the "other garbage" bin, but the recycling and reuse are strictly prohibited.

The guidance from the CDC, the Occupational Safety and Health Administration, and a few state agencies of the US shows that the waste with potential risk of COVID-19 contamination should be managed like any other MSW. The fact sheet for Oregon, US—Managing COVID-19 Solid Waste—also notes that the state's rules generally consider PPE waste, cleaning, and disinfection waste (outside the medical and healthcare industry) as general solid waste (PeRKINS Coie, 2020).

Compared with some of the treatment methods for PPE waste, the effective collection could play the most important role in waste management. The used masks, if incorrectly disposed of—e.g., in open landfills or waters, will likely degrade into smaller plastic pieces, even microplastics. During a survey on the Soko islands, masses of surgical masks were found along the shoreline (OCEANSASIA, 2020).

3.2.2 MSW collection and recycling

Although the ratio of waste that may contain viable SARS-CoV-2 is lower in MSW than in medical waste, its infectious risk cannot be ignored. MSW management differs depending on whether there are confirmed or suspected cases within a household. Most countries, such as in Romania (Mihai, 2020), follow the guidelines from UNEP and ECDC. In Italy, according to the Italian Health Institute guidelines (ISS, 2020), the MSW from a dwelling place with an infected person must be regarded as the residual MSW and disposed of in a separate bag. If there are no infected persons in the dwelling place, the household can continue to carry out undifferentiated collection just as before the pandemic.

Many countries have reached a consensus that the recycling process has very low risk and that the recyclable waste is unlikely to be infected with coronavirus. Thus, waste collection and recycling can be processed by the original process before the pandemic, but if the waste is contaminated, it must be collected in sealed bags or containers (Ikiz et al., 2021; Finnish Government, 2020; Swedish EPA, 2020). In Finland, this situation will not lead to changes in current household classification practices. The health authorities in Germany classify the transmission risk of waste collection and disposal as low (Waste Minz, 2020).

In China, the suspected and confirmed patients are concentrated in special places. Thus, the possibility of infectious waste from households is lower, and the primary need is the effective management of PPE waste. For such areas like China, the classification and recycling of MSW is not necessary. However, in some countries—those with an excessive number of patients or a lack of sufficient medical resources—or in areas where a policy of keeping patients at home is adopted, the infectious wastes, such as those that may be contaminated with bodily fluids and protective equipment, need to be separately bagged.

In other places, local authorities have suspended the part of waste recycling in some stages. A non-statutory guideline from the British Government gives the guidance on waste collection priorities during the coronavirus pandemic (Fig. 4)(GOV.UK, 2020a).

4 Rethinking effective waste management under the COVID-19 pandemic

4.1 National medical waste capacity assessment

There is no singular solution; for different countries or regions varying in number of infected cases, medical resources, isolation measures, and waste types, different solutions should be adopted. There are many challenges in dealing with timely and effective waste management. The management of medical waste involves many departments and a large number of individuals, requiring interdepartmental collaboration. In order for a country to determine whether it is capable of managing a significant increase in medical waste generation, it should compile a summary of the existing policies, regulations, and infrastructures, as well as its current operation status for dealing with medical wastes. For many developing countries that may not have detailed or adequate policies, policies and guidance from international institutions on medical waste can be adopted. The real problem is not, therefore, how to formulate these policies but how to successfully implement them. That requires mobilizing government efforts and resources. When the medical waste disposal capacity cannot be improved quickly enough, adequate disinfection should play a more important role.

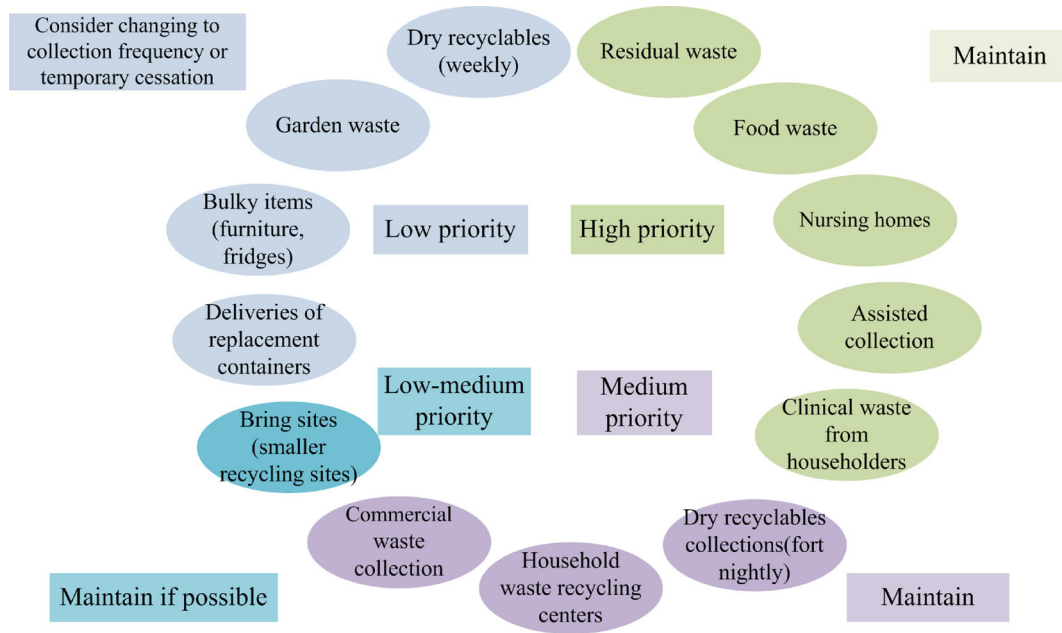


Fig. 4 Guidance on waste collection priorities (extract from the guidance of the Department for Environment Food and Rural Affairs, GOV.UK,2020a).

4.2 MSW classification, recycling and recovery

Waste collection have been influenced due to the decreasing staff availability. The suspension of recycling activities in some regions has resulted in an increase in mixed waste, creating some serious challenges to waste classification habits and the recycling industry. Citizens need to be informed whether it is necessary to continue the source separation of MSW, and recycling services should be restored as soon as possible. A large number of informal recyclers, throughout the world, are facing the exposure risks because of lack of the protective masks or gloves and safety awareness. Governments need to be aware of this category of waste processors and implement the effective strategies to control the potential risks. In many places, MSW management problems may have shifted to rural areas. For example, just before the French adopted lockdown measures, many urban residents moved to their secondary rural residences, increasing the pressure on rural waste management capabilities (Dente and Hashimoto, 2020).

4.3 Plastic waste reduction and management

The COVID-19 pandemic has increased reliance on single-use plastics (for example, increased demand for single-use bags and PPE products), and also led to a reversal of policies on source reduction of single-use plastic products. Under the COVID-19 pandemic, some systemic fragilities in waste management were uncovered. Some statewide, municipal, and corporate entities in the US and Canada suspended or postponed the single-use plastic bans. And

since the start of the pandemic, many grocery stores have forbidden the consumers to use their own reusable bags (single-use plastic bags instead) (Vanapalli et al., 2021; Ikiz et al., 2021). Thus, it is necessary to regain the latest progress in phasing out excess single-use plastic. It is particularly important to reduce the demand for new PPE and reuse it instead. PPE reuse is a potential short-term solution during the COVID-19 pandemic, which could reduce waste generation. The United States and Ireland have carried out some work in this area (Rowan and Laffey, 2020).

4.4 Updating strategies for medical waste management

Since medical waste management systems are designed for normal operation, the medical waste during an epidemic can far exceed the available capacity. Indeed, the surge in medical waste may greatly bring the pressure on a country’s comprehensive deployment capacity. In this critical situation, whether to use MSW incineration capacity to deal with medical waste is still an open question. Some countries have therefore developed auxiliary facilities, such as the fixed, mobile, and co-processing equipment. However, when using co-processing facilities, the operation must meet the standard emission requirements, in order to avoid secondary health effects. After the pandemic subsides, however, some countries will be faced with the problem of how to deal with these extra capacities. These treatment facilities are unlikely to be transformed into incinerators from which heat energy could be recovered, nor are they likely to be used for MSW. The strategies and plans for emergency

medical waste disposal will therefore need to be updated both during and after the pandemic.

5 Conclusions and future outlook

WHO states that the COVID-19 pandemic will persist for a long time, and all countries are working on prevention plans, as well as vaccine research and development. The spread of the COVID-19 pandemic will also have a long-term impact on environmental sustainability. According to the above results, there is no doubt that the COVID-19 outbreak has greatly increased the amount of medical waste, especially infectious medical waste. In many countries suffering from COVID-19, their waste has an increase with 18%–425%. From Jan 22 to Sep 22, 2.9 million tons of COVID-19-related medical waste has been generated.

Meanwhile, the consumers have shifted from worrying about plastic waste's environmental impacts to preferring plastic packaging during the pandemic. The pandemic has also increased their demand for online shopping and food delivery services. These consumption habit changes have without exception resulted in plastic waste management difficulties and a reversal of policies on source reduction of single-use plastics products. The quarantine policies and lockdowns have probably increased the volume of food waste, but perhaps also helped them realize the importance of food waste reduction. Furthermore, any increased food waste in households may have been offset by a reduction outside the household, especially from commercial food services. Even, food loss and waste may actually decrease.

Many countries have adjusted or updated their policies for emergency waste management under the COVID-19 attack. And China can provide valuable lessons from their experiences: building a comprehensive disposal system through a combination of centralized disposal and on-site emergency disposal of medical waste, such as mobile treatment equipment and industrial kilns for medical waste disposal. Apart from medical waste, the collection, recycling, and treatment practices for household waste vary in different countries and cities. Depending on the proportion and possibility of potential infectious waste in MSW, the appropriate strategy should be selected for dealing with this waste.

The pandemic not only changed individuals' lifestyle and consumption patterns but also stimulated more thoughtfulness on the relationships between human and natural environment. This study provides basic information on the effective solid waste management during and after the pandemic. Limited by the current situation, previous studies have focused on the description of the COVID-19 impact on waste generation, while studies on the deeper impacts are still lacking. More investigations are required to evaluate the changes in waste characteristics, overall environmental impacts, consumption of

resources and long-term effects. In addition, there are serious questions about whether the previous systems of classification, recycling and resource recovery can be quickly restored, and whether the population will again focus their concern on reducing plastic waste. Issues like these need to be discussed and studied in the future.

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