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Municipal solid waste management under COVID-19: challenges and recommendations

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COVID-19 is proving to be an unprecedented disaster for human health, social contacts and the economy worldwide. It is evident that SARS-CoV-2 may spread through municipal solid waste (MSW), if collected, bagged, handled, transported or disposed of inappropriately. Under the stress placed by the current pandemic on the sanitary performance across all MSW management (MSWM) chains, this industry needs to re-examine its infrastructure resilience with respect to all processes, from waste identification, classification, collection, separation, storage, transportation, recycling, treatment and disposal. The current paper provides an overview of the severe challenges placed by COVID-19 onto MSW systems, highlighting the essential role of waste management in public health protection during the ongoing pandemic. It also discusses the measures issued by various international organisations and countries for the protection of MSWM employees (MSWEs), identifying gaps, especially for developing countries, where personal protection equipment and clear guidelines to MSWEs may not have been provided, and the general public may not be well informed. In countries with high recycling rates of MSW, the need to protect MSWEs' health has affected the supply stream of the recycling industry. The article concludes with recommendations for the MSW industry operating under public health crisis conditions.

1. Introduction

The explosive growth of the world's population in the last century, which is crowded in high-density cities; the difficulty in managing solid and liquid waste, the quantities of which keep on increasing despite all recycling efforts (Eurostat, 2020a; US EPA, 2014); and the pollution of many of the planet's systems, among others, make for a dangerous mixture of conditions for the humankind in the case of epidemics and pandemics. Furthermore, climate change is expected to influence the seasonal and geographic distribution of vector-borne diseases, which does not bode well for virus-transmitted respiratory diseases when this is combined with indications that a worsening of allergic and asthmatic conditions is also expected to occur (US National Academies of Sciences, Engineering, and Medicine, 2015). In a remarkable foresight related to the COVID-19 pandemic, one of the key findings of a 2015 US National Academies of Sciences, Engineering, and Medicine report of the impact of climate change on human health, was that 'climate change will interact with other driving factors (such as travel-related exposures or evolutionary adaptation of invasive vectors and pathogens) to influence the emergence or re-emergence of vector-borne pathogens [High Confidence]' (US National Academies of Sciences, Engineering, and Medicine, 2015, Key Finding 5, p. 20).

Thus, the current severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has appeared as a highly pathogenic strain of the newly emerged coronaviruses, following the SARS-CoV-1 and the Middle East respiratory syndrome (MERS-CoV) coronaviruses in the past two decades (Li *et al*., 2005; WHO, 2019). COVID-19 was declared a pandemic by the WHO Director General on 11 March 2020 (WHO, 2020a), and since then it has initially created a health, and subsequently, an economic crisis worldwide.

Municipal solid waste (MSW) has been recognised as a source of (*a*) faecal coliform bacteria, salmonellae, human enteroviruses and protozoan parasites, originating from human and pet faeces, as well as human noroviruses, from biosolids derived from wastewater treatment sludge (Gerba *et al*., 2011); (*b*) antibiotic-resistant bacteria, which have been found in the ambient air downwind of waste-to-energy (WtE) or landfill sites (Li *et al*., 2020); (*c*) Hepatitis B virus, at a higher prevalence, relative to the general population, in MSW employees (MSWEs) due to their exposure to sharp objects in the MSW stream (Ansari-Moghaddam *et al*., 2016; Corrao *et al*., 2013); and (*d*) general health problems in MSWEs, which are exhibited through respiratory symptoms, lung function impairments, infections and inflammations, low haemoglobin and erythrocyte levels and so on (Abdulah *et al*., 2020; Athanasiou *et al*., 2010; Keesstra *et al*., 2016, 2018; Ray *et al*., 2005; Rodrigo-Comino *et al*., 2018; Visser *et al*., 2019).

Kampf *et al*. (2020) compiled several studies on human coronaviruses (HCoV), which indicated that these can remain infectious on various surfaces (steel, aluminium, plastic, PVC, ceramic, Teflon, metal, wood, glass and paper/cardboard (Duan *et al*., 2003)), as well as on latex gloves and gowns (Lai *et al*., 2005; Sizun *et al*., 2000) from 2 h to 9 days (Figure 1). Higher temperatures decreased the duration of persistence. van Doremalen *et al*. (2020) compared the aerosol and surface stability of SARS-CoV-2 relative to SARS-CoV-1 and found that the new strain exhibited similar stability to that of SARS-CoV-1 and, furthermore, that 'the virus can remain viable and infectious in aerosols for hours and on surfaces up to days'. Evidence of SARS-CoV-2 RNA has been found in faeces and blood (Xiao *et al*., 2020; Zhang *et al*., 2020), and the sewage of several cities (Lodder and de Roda Husman, 2020), thus indicating that it can enter the MSW stream. In addition, a multitude of items, most prominently face masks and gloves, and also several general use items, which have come into contact with infected people, have been discarded and have become part of the landfilled or incinerated MSW. Hence, the presence of SARS-CoV-2 in MSW is a public health consideration for all chains of the MSW industry (environmental authorities and agencies; municipalities; MSW collection, transportation and disposal companies; managers, engineers and MSWEs across the whole spectrum of this industry's activities, etc.).

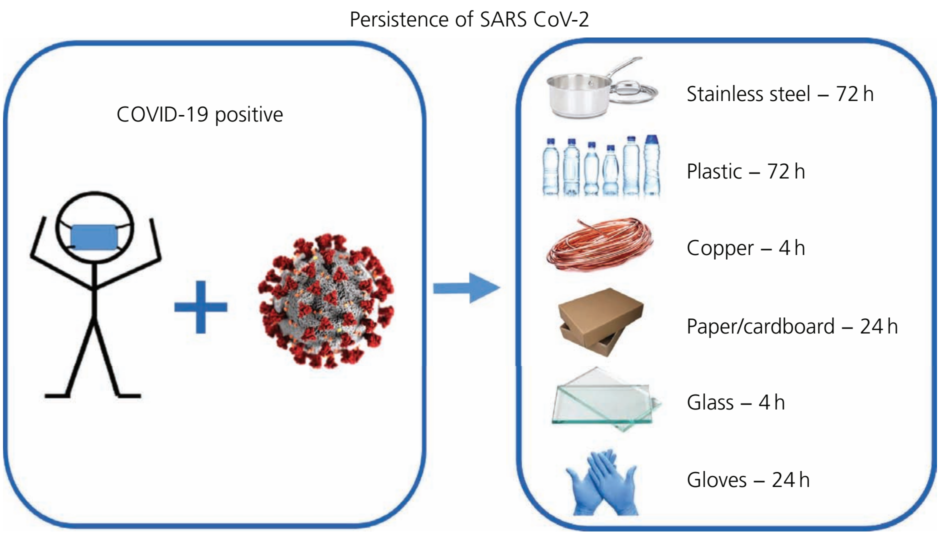

Figure 1. Resilience of SARS-CoV-2 on different surface (data were taken from Sharma *et al*. (2020), Suman *et al*. (2020) and van Doremalen *et al*. (2020))

It is evident that the COVID-19 pandemic may spread through MSW, if collected, bagged, handled, transported or disposed of inadequately (Mol and Caldas, 2020). It is pertinent therefore to analyse (*a*) the types of MSW and high-risk areas in a city or a region, where special measures must be implemented, for the protection of MSWEs during collection and transportation of the waste; (*b*) the potential temporary storage of infected MSW (IMSW) during pandemics in order to alleviate the pressure on medical incinerator facilities; (*c*) the upgrading of safety measures in landfill and WtE operations; and (*d*) the updating of policies and guidelines to safely manage MSW during pandemics.

The International Solid Waste Association (ISWA) has considered three overall priorities for solid waste management (SWM) during the COVID-19 pandemic: (*a*) ensure that the operation of recycling services, treatment and disposal facilities will not get disrupted, and no additional risks to the public health will be created by improper management; (*b*) adjust recycling activities to avoid cross-contamination and infections; and (*c*) ensure that healthcare and medical waste (H&MW) will be safely treated and disposed of, making sure there is no risk for further infections and pollution (ISWA, 2020). Some of the common methods for inactivation of pathogen(s) in solid waste (SW) are incineration, steam treatment technologies (autoclaves and hydroclave), chemical (for small quantities) and microwave treatment. On dealing with the safe management of MSW during the COVID-19 pandemic, the issue of increased quantities of H&MW during these times, of MSW cross-contaminated by infected items and of the existence of sufficient capacity in facilities that handle such waste is raised.

Under the stress placed by the current pandemic on the sanitary performance across all SWM chains, this industry needs to re-examine all processes involved, from waste identification, classification, collection, separation, storage, transportation, recycling, treatment and disposal, as well as its infrastructure resilience. The current article conducts a comprehensive review of current SWM practices in order to assess potential weak links related to COVID-19 and to establish strategies for effective management during this and future pandemics (Figure 2). Thus, the main aims of this paper are to (*a*) critically review the information regarding the sources, generation, collection and storage of IMSW under the existing SWM system; (*b*) assess the technical capabilities of MSW-disposal installations, in particular, for developing countries; (*c*) determine the potential threats due to open dumping and landfilling of IMSW; and (*d*) establish strategies and provide suggestions for effective SWM during this and future pandemics.

2. SWM challenges during the COVID-19 pandemic

2.1 Sources, collection and transportation of infectious MSW during COVID-19

The criticality of SWM to prevent the spread of diseases is well established historically (Paleologos *et al*., 2020). This is more so for developing countries, where managing MSW in a sanitary way is limited in many cases to only 30–35% of the population, living primarily in urban areas. Owing to the strong infectivity and pathogenicity of SARS-CoV-2, this has brought many new challenges to the SWM industry, and improving overall practices across all the SWM chain is a crucial aspect to prevent and control the pandemic (Tang *et al*., 2020). Figure 3 illustrates the chains in the medical, household and street SWM systems, all of which can constitute exposure routes and entry points of the virus in the environment.

An important stream of SW is H&MW, which is primarily categorised into non-hazardous and hazardous waste. In developing nations, the respective quantities vary from 35 to 98.7% for the non-hazardous component and from 1.3 to 65% for the hazardous one, depending on socio-economic conditions and per capita gross

Figure 2. Waste management strategies during this and future pandemics

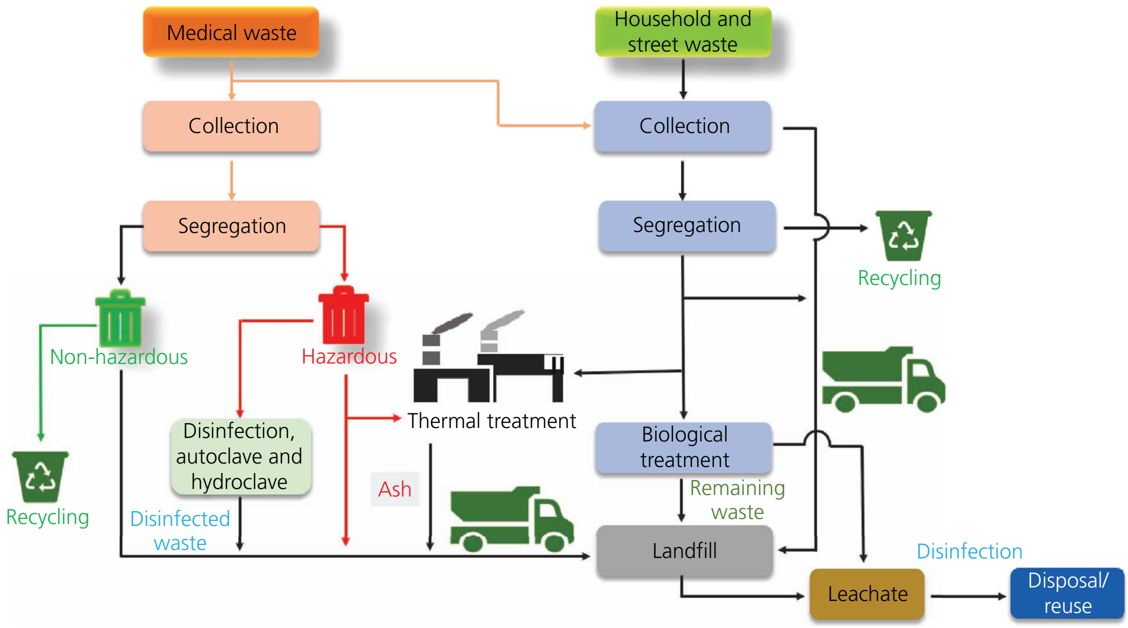

Figure 3. Potential entry points of infectious waste in the MSW management stream

domestic product (Ansari *et al.*, 2019; Costa *et al.*, 2019). Hazardous H&MW should be disposed of in medical incinerators, and if found in MSW landfills, this is due to inappropriate disposal at general-waste collection points or to unscrupulous contractors attempting to take advantage of the difference in tipping fee between landfills and incineration facilities.

SARS-CoV-2-contaminated H&MW may task the capacity of available medical incinerators due to a large number of hospitalised patients and the volume of infectious waste generated. On the other hand, in some countries, such as the Czech Republic and Poland, there has been an almost 90% decrease in the number of surgeries during the pandemic, which may have led to a reduction in the amount of H&MW there. Our analysis of the infectious medical waste (MW) from a clinic in Poland showed that these had dropped during the pandemic, which was related to the closure of multiple hospital wards and the non-admittance of non-COVID-19 patients in the clinic. Figure 4 summarises our data from this clinic and shows that compared to the pre-COVID-19 conditions of February 2020, the mass of waste decreased by about 4% in March, by over 37% in April and by about 14% in May 2020. An increase in the amount of waste was observed during the first days of June, resulting from partial restoration of previously closed clinical wards and the admittance of non-COVID-19 patients. This is likely to continue over the next months with similar trends observed in other hospitals in Poland.

It is interesting to note that for this clinic in which Figure 4 shows a decrease in the mass of MW, the corresponding volume during the period of February to April 2020 remained constant, while it increased significantly in May. This is due to the fact that the MW during the months of this COVID-19 peak in Poland consisted primarily of disinfectant liquids, protective suits, disposable gloves and other protective equipment against the infection, which occupy a large volume relative to their weight. This relative increase in the volumes of the MW generated during these months also resulted in a rise in space requirements at the clinic, because according to Polish regulations, MW generated during the COVID-19 pandemic needed to be stored and isolated for at least 72 h on-site, before being transported for recycling or incineration.

In many countries, there were regions without or very few confirmed infected cases. In these instances, MSW can be treated as usual, with normal working procedures. For areas where large numbers of confirmed cases have been reported, trained crews, disinfection of the MSW and special transportation routes may be considered. At neighbourhoods with high numbers of infected cases, this can be combined with targeted testing (Chandana *et al.*, 2020; Liu *et al.*, 2020) of the fractions of waste that are most likely to have the virus, such as used masks, gloves, tissue papers and diapers in order not to unduly burden medical incinerators. In certain countries, such as the UK, public health agencies have recommended that all waste that has come into contact with self-isolating individuals should be double-bagged, stored for 72 h and only released to the general waste if the individuals' test results return as negative (Langley, 2020; ACR, 2020). In hot spot areas, sealing refuse bags and disinfecting waste collection locations, containers and vehicles after each collection event may be considered. Handling of sealed MSW should be done with due care to ensure that no MSWE exposure occurs during the process of compaction (when rear-end loaders or portable compactors are used for collection). For example, in Singapore, many of the construction workers' dormitories had been designated as

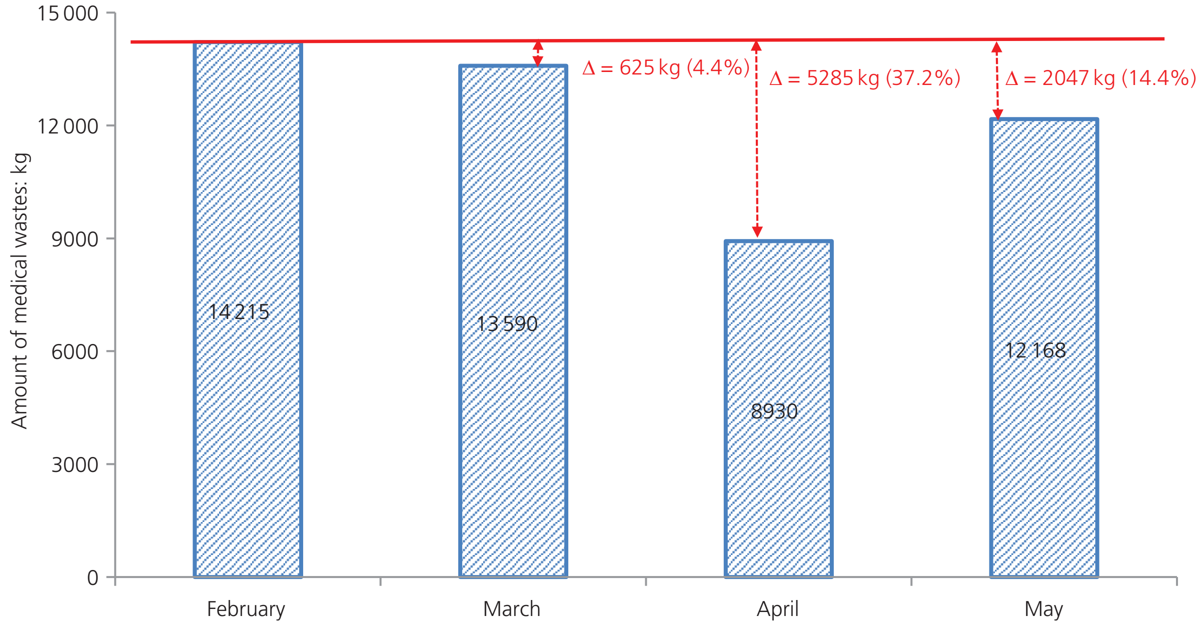

Figure 4. Medical waste generated by a clinic in Poland during the 2020 months of the COVID-19 spread

quarantine zones, and waste from these locations were delivered in sealed refuse bags to the collection truck, thus ensuring that MSWEs were not exposed to infected waste. The frequency of waste collection from such areas had increased to up to three times daily, in order to reduce the risk of infection.

During the COVID-19 pandemic, infected people self-isolating at home generate pathogen-laden household items, which can result in the contagion of the bulk of MSW. This can pose threats, especially in cases where (*a*) collection is done by untrained/unskilled personnel who do not take appropriate precautions, (*b*) inadequate number of bins exist in a neighbourhood (Odonkor *et al.*, 2020; Saadat *et al.*, 2020), and (*c*) contaminated items, such as masks, gloves and others, get to be thrown out in the streets (Ritzkowski, 2020).

SARS-CoV-2-contaminated waste may pose health hazards especially to MSWEs, who may be exposed to contaminated bioaerosols (Carducci *et al.*, 2013; Tian *et al.*, 2020) and items from infected people. In several European countries, MSW rules during the pandemic differentiate between the collection and treatment of items coming from households with infectious cases and from the general population (Figure 5). In developed

Figure 5. MSW practices during the Covid-19 crisis in March 2020 (Modified from ACR (2020))

countries, public space disinfection, broad distribution of free sanitisers and strict guidelines and procedures make the spread of infection to MSWEs extremely low, if sufficient care is exercised by them. Thus, the ISWA has issued a number of measures to be taken by MSWEs during the pandemic, including the following: using face and eye protection and puncture-resistant gloves, wearing disposal gloves under the work gloves, changing daily uniforms and work shoes and washing them above 60°C, avoiding any contact with residents during the collection process, having disinfectants in every collection vehicle, sanitising the driver's cab after each work cycle and also applying all rules applicable to the general public, such as social distancing and frequent handwashing (Mavropoulos, 2020). Many countries, recognising the important role of MSWEs, have provided them a 'key worker' status, for example, in the UK, educational and care provision benefits are provided to their children during the pandemic (Langley, 2020).

In the USA, the Occupational Safety and Health Administration (OSHA) has assessed as low risk the activities that are associated with handling municipal and recyclable waste, as well as the equipment maintenance in the waste and recycling industry. Handling waste from healthcare facilities that have treated COVID-19 patients is classified by OSHA as medium risk (OSHA, 2020). This risk level assessment in the USA is related to the fact that MSWEs there are provided with personal protection equipment (PPE), and detailed administrative and engineering controls and safe work practices exist, which must be followed throughout the SWM industry's chains.

2.2 Treatment and monitoring of virus-contaminated waste

At medical facilities, infectious and pathological wastes are required to be stored separately from other hazardous waste, at temperatures no higher than 8°C, to slow down or prevent their decomposition. If refrigeration is not available, storage times should not exceed 24 h during the hot seasons and 48 h during the cold seasons, in warm climates, with these times extending to 48 h and 72 h, respectively, in temperate climates. Currently, there are generally two main disposal methods for MSW contaminated by viruses (Tang *et al.*, 2020): (*a*) conventional treatment methods, such as disinfection, microwave, sterilisation and safe landfilling and (*b*) high-temperature treatment methods, such as incineration, pyrolysis and gasification. Some promising innovative technologies exist, such as the arc plasma technology, where temperatures over several thousand degrees Celsius are achieved. However, presently, these are restricted to a few facilities worldwide (Bratsev *et al.*, 2006).

For infectious waste, treatment technologies should be able to achieve inactivation of vegetative bacteria, fungi, lipophilic/hydrophilic viruses, parasites and mycobacterium at a 6 $\log_{10}$ (99.9999%) reduction, or greater (Bagchi, 2004). Furthermore, inactivation of *Geobacillus stearothermophilus* and *Bacillus atrophaeus* spores should be at a 4 $\log_{10}$ (99.99%) reduction, or higher (Bagchi, 2004). Table 1 provides an overview of the approved disposal methods suitable for infectious and pathological wastes. As it is evident from Table 1, for infectious waste, incineration, chemical (for small quantities), autoclave (at gauge pressure between 100 and 200 kPa) and microwave are the recommended treatment methods. Shredding of SW before or during disinfection is necessary to ensure good contact between the disinfectant and the waste particle surfaces, and this should be done in a closed system to avoid the release of pathogens/viruses into the atmosphere. Microwave units with internal shredders can theoretically be used for pathological waste, which is equivalent to hybrid autoclaves and continuous steam treatment systems with internal shredders. Although microwave and disinfection methods can kill bacteria and other microorganisms, their capacity and reduction effect need to be further investigated.

In some countries, during the COVID-19 pandemic, due to the volume of contaminated or suspected to have been contaminated MSW and MW, and the small number of medical incineration facilities existing, regular WtE plants may be used. In such cases, because waste is dumped into waste bunkers that are kept at negative pressures, the likelihood of the COVID-19 virus spreading out from the bunkers is negligible. Nevertheless, due care should be exercised to ensure no major maintenance activities are carried out in the waste bunkers during the pandemic.

Municipalities in developing countries or those having low budgets for MSW have relied on landfilling rather than WtE because of the lack of national or local policies that would provide incentives for transitioning to the more costly WtE treatment technologies relative to landfilling, and/or the high percentage of organic matter (OM) with high moisture content in their MSW stream (Datta *et al.*, 2018; Ma *et al.*, 2020; Paleologos *et al.*, 2018; Saadat *et al.*, 2020; Siddiqi *et al.*, 2020). Owing to these

Table 1. Treatment technologies for infectious and pathological wastes (UNEP Basel Convention, 2020)

Waste category	Incineration using best available techniques (BAT)	Chemical disinfection	Autoclave	Microwave	Encapsulation	Specially engineered landfill	Discharge to sewer systems
Infectious waste	Yes	Small quantities	Yes	Yes	No	No	Only urine and faeces
Pathological waste	Yes	No	No	No	No	No	No

challenges, thermal treatment does not usually exist in many developing nations, and biological treatment (composting, anaerobic digestion and bioreactor landfills) of MSW is prevalent (Chembukavu *et al*., 2019). In the absence of thermal treatment, or when the amount of H&MW generated during a pandemic is much more than medical incineration facilities can cope with, sanitary landfills become an even more important aspect of SWM. The existence of IMSW in the general MSW stream has the potential to contaminate the environment, the air and rodents or birds that may be attracted, between the time of MSW disposal and the clay cover deposition at the end of a working day. To avoid such eventualities, MSW from known hot spots may be disinfected. In developing countries, heat treatment at approximately 60°C for over a 15 min duration would be a prudent option to inactivate the virus (Wang *et al*., 2020; WHO, 2020b).

In regions where WtE plants are not available, one possible solution for the disposal of IMSW can be to collaborate with neighbouring municipalities that may have both a low volume of IMSW and some form of heat treatment available. If no thermal treatment option exists, then IMSW may be buried in landfills, ensuring that MSWEs are not exposed during handling and waste is covered by clay at more frequent intervals than the once-a-day normal procedure. The rapid increase of SW during the pandemic has burdened many disposal sites, some of which were already operating at design capacity. For example, the landfill in Changsha, the capital of Hunan Province, China, which began operation in 2003 had already exceeded, prior to COVID-19, its design elevation. Yu and Dhong (2020) estimated that in the past years in China, MSW generation rose by about 40%, from about 154 Mt in 2008 to 215 Mt in 2017. Although China has set a target to increase its incineration rate in the next 5 years by more than 50%, the majority of the cities there will still be served by landfills.

For cities/regions where the capacity of landfills and WtE plants proves to be insufficient during the pandemic, possible solutions include the following: (*a*) temporary storage sites can be constructed, where IMSW can be stored in sealed containers after disinfection, with technical specifications put in place to address health- and environmental-related problems; (*b*) IMSW collection and disposal procedures can be incremental based on health risk level, viral load and type of waste per area; (*c*) specific sites or facilities, such as abandoned quarries/pits, industrial kilns and cement factories, may be used as standby facilities for IMSW disposal during emergencies; and (*d*) promoting public awareness campaigns about the importance of disposing IMSW separately from regular household waste.

For IMSW disposed of in landfills during the pandemic, waste should be unloaded as close as possible to a landfill cell that has, perhaps, been designated only for IMSW, thereby avoiding this waste from being mixed with general MSW. In this context, the specifications of liner and cover materials used in landfills exist that minimise global, superficial, sliding, rolling, puncher and pull-out failures and settlement of all components (e.g., Long *et al*., 1993; Oweis, 1993; Zamiskie *et al*., 1994). At the same time, for the acceptance of IMSW in landfills during emergencies, geosynthetic clay liners (GCLs) with leakage detection systems may be installed that would allow monitoring liner and cover system performance. The leachate of landfills accepting IMSW during the pandemic should be carefully processed to avoid aerosol formation during aeration or flushing in the leachate treatment plant. Recent studies (Liu *et al*., 2020) have reported the presence of SARS-CoV-2 in aerosols. It may even be prudent to disinfect leachate from such landfills by employing one of the standard methods of conventional disinfection (Wang *et al*., 2020) or other appropriate techniques, such as solar water disinfection and photocatalytic agents (zinc oxide (ZnO), zinc oxide(1−) (ZnO^-), silver (Ag)–zinc oxide nanoparticles) (Danwittayakul *et al*., 2020), carefully chosen to avoid corrosion of leachate transmission lines. Cohesive soil liners or cut-off walls may be employed to protect the environment from hazardous substances emanating from landfills with leachate (Koda and Osinski, 2017; Vaverková, 2019; Vaverková and Adamcová, 2014). As an example, cut-off walls were implemented at an old embankment-type landfill in Poland, which lacked contamination protective systems, resulting in improvements in groundwater quality (Koda *et al*., 2013, 2016).

At the same time, more advanced modelling studies should be conducted to investigate plume evolution in order to assess the probability of groundwater contamination (Lerche and Paleologos, 2001; Singh, 2019). It must be borne in mind that depending on a number of factors that include the heterogeneity of the subsurface environment, the nature and quantity of the contaminants, the location of the cell where leakage has occurred, the design of the monitoring well network and the frequency of sampling, detection of the contamination may not be achieved through the samples taken at the monitoring wells (Papapetridis and Paleologos, 2011a, 2012). Figure 6, from Papapetridis and Paleologos (2011b), indicates a strong dependence of the probability of detection, P_d, on the frequency of sampling and the number of monitoring wells in heterogeneous subsurface media (variance of ln K is equal to 1, where K is the hydraulic conductivity, and the transverse dispersivity, a_T, equalled to 0.2 m). One should notice that for the regular sampling frequency, for example, recommended by the US EPA of once every 6 months, even for an extensive number of monitoring wells, such as the 20 wells shown in Figure 6, and at optimised distances from a landfill, the probability to observe a leakage from a landfill cell may be close to only 50%.

3. Factors affecting virus migration and activation in environmental media

The assessment of risk to human health due to virus migration through the bottom lining systems of modern landfills, which comprise a synthetic geomembrane (GM) layer overlying a low-permeability mineral layer that, in turn, consists of a compacted clay liner (CCL) or a GCL, requires modelling of pathogen transport through the engineered barriers and the underlying

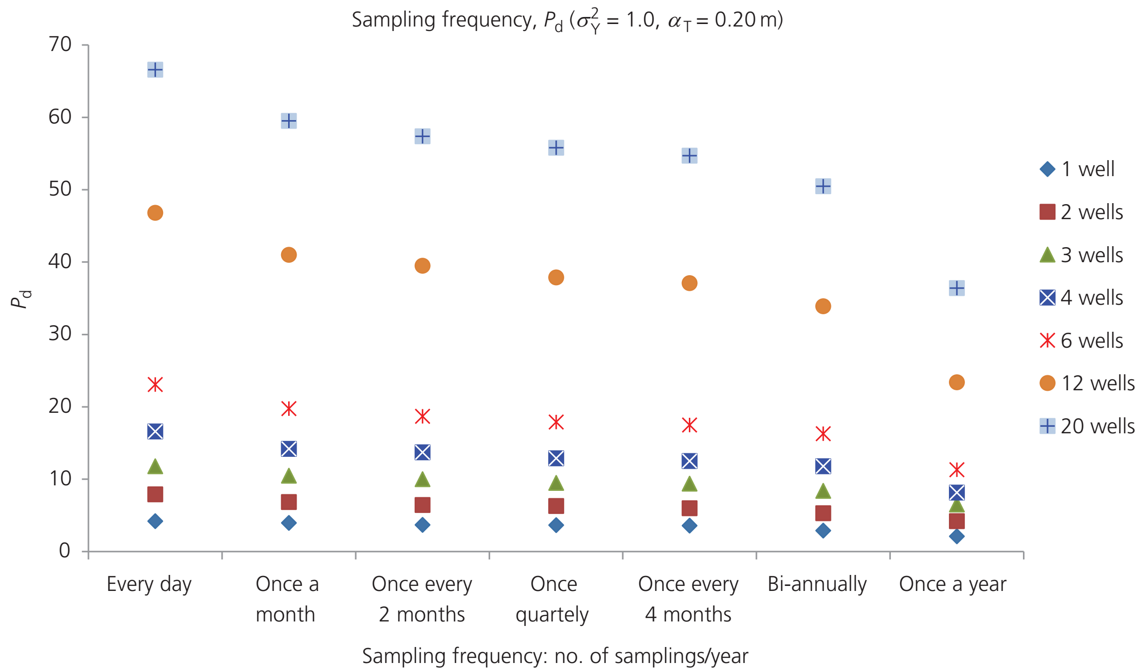

Figure 6. Probability of detection, P_d, plotted against the frequency of sampling for a mild heterogeneous medium (variance of ln *K* is equal to 1, where *K* is the hydraulic conductivity and transverse dispersivity, α_T, is equal to 0.2 m) for several configurations of monitoring wells (Papapetridis and Paleologos, 2011b)

aquifers (Mohamed and Paleologos, 2017). This would aim to predict virus concentrations in the groundwater at specified compliance points downstream of a landfill (Dominijanni and Manassero, 2019; Guarena *et al.*, 2020). While virus migration through the GM layer of a composite liner is governed by the same mechanisms of inorganic chemicals, as the relatively wide dimensions of viruses cause an extremely slow diffusion, if any at all, through polymer-based barriers with preferential transport pathways via GM layer defects (Shackelford, 2014), modelling virus migration requires the physico-chemical interactions that occur between the pathogen and the soil particles at the pore scale to be taken into account.

Viruses may undergo inactivation even before interacting with the clay barrier, as specific viral components that are required for infection, such as the nucleic acid core and the outer protein capsid, on which the host-recognition sites are located, are naturally subjected to degradation. Moreover, the leachate itself may pose a harsh environment for the survival of viruses, as the aforementioned mechanisms of viral inactivation are accelerated upon an increase in temperature and a deviation from pH neutral conditions. The microbially mediated consumption of the OM determines the release of energy in the form of heat and the generation of volatile organic acids, which are responsible for the relatively low pH during the early MSW decomposition stages (Chen *et al.*, 2019). For instance, based on the results of an experimental study aimed at measuring the survival of H6N2 avian influenza virus, Graiver *et al.* (2009) calculated the persistence times within the methanogenic landfill leachate, which ranged from approximately 30 days to more than 600 days, and asserted that the decay in the concentration of the infectious virus could be modelled as a first-order reaction.

When pollutant transport through the clay barrier is considered, the ability of viruses to be reversibly adsorbed on clay particles should be accounted for in mass balance equations between liquid and solid phases. Such attachment and detachment phenomena are governed by electrostatic forces, as the protein capsid of viruses carries a net electrical charge due to the ionisation of carboxyl, amino and other functional groups (Harvey and Ryan, 2004). The virus' net electrical charge strongly depends on the pH of the pore solution, and, therefore, it is characterised by an isoelectric point (pI) – that is, the pH value at which the net electrical charge results to be null. Above the pI, the number of deprotonated carboxyl groups exceeds the number of protonated amino groups and the sign of the virus surface charge is negative, whereas the opposite situation is encountered below the pI value. Based on the typical values that are assumed by pI, which usually falls in the 3.5 to 7 range (Michen and Graule, 2010), viruses are negatively charged under neutral conditions. This result is confirmed for SARS-CoV-2 by the measurement of a relatively high value of pI, equal to about 6.2, reported by Calligari *et al.* (2020). Because clay particles are also characterised by a negative charge under neutral conditions, the system would remain stable and unfavourable to pathogen adsorption, unless there is an increase in the electrolyte concentration (Sadeghi *et al.*, 2011) or the electrochemical valence of the cationic species that are dissolved in the pore solution (Sadeghi *et al.*, 2013). These conditions would cause a compression of the diffuse double layer and a reduction in the electrostatic repulsive forces between mineral surfaces and viruses, enabling them to approach each other as a result of the overwhelming van der Waals forces (Syngouna and Chrysikopoulos, 2010; Theng, 2012).

The adsorption process described above should not be regarded as providing the definitive conditions for complete immobilisation of the virus within the clay barrier, since a perturbation in the chemical composition of the permeating solution (e.g. decrease in the ionic strength) can lead to fast detachment of the adsorbed pathogens. These complexities make quantification of the pathogens' survival when attached to geologic media uncertain – that is, whether their inactivation rate is decreased or increased with respect to free-solution conditions.

Inactivation of viruses is slowed when they get attached to porous media with a high content of clay minerals (Harvey and Ryan, 2004). In contrast, inactivation increases when viruses are adsorbed on coarse-grained soils with a high content of iron and aluminium oxides, due to an alkaline pI (Straub *et al.*, 1992). In the former case, both adsorbate and adsorbent carry a net negative electrical charge, and thus, the interaction forces are relatively weak. In such a case, the pleomorphic structure of many viruses allows deformation of the protein capsid to take place, in order to adapt to the clay particle surface. This mechanism provides high mechanical stability, preserving the integrity and infectiousness of a virus for a longer time than under free-solution conditions (Block *et al.*, 2016). In the latter case, the net electrical charges that are carried by adsorbate and adsorbent have an opposite sign under near-neutral conditions, so that the virus and the mineral surface are held together by strong electrostatic attractive forces, leading to a disruption of the virus structure and its inactivation.

However, an inversion in the sign of the virus' net electrical charge can take place under slight pH perturbations in the acidic side, which might be encountered in landfills during the initial phase of anaerobic digestion of the OM. Under such conditions, as the intersurface potential energy becomes negative (attractive), an enhanced virus uptake and an increased inactivation rate are expected to occur in contact with clay minerals (McLaren and Peterson, 1965). These favourable conditions for virus adsorption and degradation on the clay particle surface are further enhanced in the case of use of GCLs in the place of CCLs within composite liners. This is due to (*a*) the presence of montmorillonite, which is able to maintain an approximately stable negative net electrical charge at low pH values, and (*b*) the high cation exchange capacity (CEC ≈ 100 meq/100 g) and high specific surface area (SSA ≈ 750 m^2/g) of the montmorillonite, as compared to the kaolinite (CEC ≈ 5 meq/100 g; SSA ≈ 15 m^2/g) (Lipson and Stotzky, 1983; Theng, 2012). It is noted that the design of CCLs could be optimised for the improvement in containment performance against SARS-CoV-2 (adsorption and inactivation capacity) through the addition of amended sandy soils with a high pI, such as magnetite sands (Moore *et al.*, 1981, 1982). Care should be given to the overall hydraulic conductivity of the mix design to limit leachate transport in the subsurface environment.

A literature review of the factors affecting adsorption of viruses in soils (Kimura *et al.*, 2008) reveals that adsorption follows either the Freundlich or Langmuir isotherm (Moore *et al.*, 1981) with a number of factors affecting the survival and migration of viruses in groundwater. These include temperature, soil texture, moisture, OM, pH, cation presence, clay type and content, aerobicity, and heavy metals and acid pollutants (Keswick and Gerba, 1980; Kimura *et al.*, 2008). A number of studies have shown that temperature correlated significantly with the decay rates of several viruses, with lower temperatures resulting in longer periods of survival, probably because of lower viral activity, and hence, reduction in the decomposition and inactivation of viruses (Leonardopoulos *et al.*, 1996; Yates *et al.*, 1985). The influence of soil texture, clay type and content, and pH on the binding force between viruses and soils have been discussed extensively above. Adsorption of viruses to clay particles becomes more pronounced under higher ionic strengths because these reduce the electrokinetic potential of both clay and virus particles, whereas viral association with colloidal and particulate matter prolongs the survival and infectivity of viruses (Kimura *et al.*, 2008; Toyoda *et al.*, 1991). OM (both soil-associated and dissolved) weakens the electrostatic bonding between viruses and soils (Kimura *et al.*, 2008). Although viruses get efficiently adsorbed in soils, they can migrate distantly in horizontal and vertical directions and pollute surface water and groundwater bodies. Soil drying has been seen to affect virus inactivation significantly below a certain moisture content with evaporation being the main virucidal factor (Yeager and O'Brien, 1979a, 1979b). According to Kimura *et al.* (2008), there had not been any studies until 2008 to assess the mechanisms of toxicity of heavy metals and acid pollutants to viruses in soils.

Finally, the development of a theoretical model capable of simulating the movement of viruses through clay-based barriers should account for the typical dimensions of the concerned pathogen. The diameter of SARS-CoV-2 is ≈120 nm, which is of the same order of magnitude as the width (few tenths to several hundreds of nanometre) of the conductive pores (i.e. the void space wherein the transport of solvent and solutes takes place) of the GCL bentonite layer (Manassero, 2020). Furthermore, many experimental studies have shown that the transport of inorganic electrolytes through montmorillonite-rich clay soils is partially restricted due to the repulsive electrical forces that arise between anionic species and the negatively charged clay particles (Dominijanni *et al.*, 2018; Mohamed and Paleologos, 2017; Musso *et al.*, 2017). Because of the above, GCLs are expected to behave as semipermeable membranes for negatively charged viruses as a result of two different concurrent mechanisms: (*a*) a steric hindrance, whereby the narrower bentonite pores are not accessible by large-sized pathogens, and (*b*) an electrical hindrance, whereby the wider bentonite pores can also impose some restriction to the pathogen migration because of the overlapping of the diffuse-ion swarms.

4. Policies and guidelines, and recycling during the COVID-19 pandemic

International organisations and countries have issued numerous communiques and guidelines related to SWM services during the pandemic. The European Commission (EC) 14 April 2020 (EC, 2020) provided the following guidance in terms of SW collection. Paper tissue and face masks from infected people must be placed immediately after use in a refuse bag that is inside the patient's room. The caregiver's gloves and mask after each visit to the patient must be placed in a separate bag, which must be located outside of the patient's room. Both bags must be individually tied and inserted into a clean general-waste bag, never emptying their contents into the latter. The general bag should be treated as regular MSW and no special disposal or collection measures need to be taken. In terms of healthcare facilities, the relevant law is the European Directive 2008/98/EC on waste (European Parliament and Council, 2008), as interpreted for the circumstances of the pandemic by the European Centre for Disease Prevention and Control (ECDC, 2020a) in various updates. The 13 May 2020 guidance by ECDC (2020a) recommended that those healthcare facilities' staff 'engaged in environmental cleaning and WM should wear a surgical mask, gloves, eye protection (visor or goggles) and a gown', and regular cleaning and disinfection of the facilities, and in particular, of the patients' rooms, should be performed. The wastes generated should be regarded, during their transportation, as infectious clinical waste Category B (UN3291: clinical waste) (WHO, 2012), in terms of their packaging, labelling and documentation requirements, and ECDC (2020b) specialised these transportation regulations in the context of the COVID-19 pandemic.

EU member states adapted the EC's and ECDC's recommendations to their particular SWM industry's characteristics (existence and capacity of WtE facilities, extent of recycling, etc.). Some European countries faced problems related to their SWM industry during the initial phase of the pandemic. This was due to the fact that they had been exercising a very high level of recycling (Figure 7), which during the pandemic conflicted the manual handling done along all chains of the recycling industry with the need for protection of employees since SARS-CoV-2 was found to survive on material surfaces (van Doremalen *et al.*, 2020). Although most recycling facilities rely on automated operations (magnetic, mechanical and optical methods) to separate various content for reuse, human presence is needed for quality control and occasional manual sorting. Thus, for example, in plastic recycling plants, workers must oversee the operation of conveyor belts and manually remove unwanted materials.

In Europe, some countries (Figure 7, based on the most recent EU data (Eurostat, 2020b)), such as Belgium, had already met in 2013 the 50% recycling target for MSW set by the EU Waste Framework Directive (EEA, 2013b) and had even set a target of zero waste. Norway, one of the most advanced countries in SWM in the world, had about 40% of its waste recycled, 50% incinerated and only 6% ending in landfills (EEA, 2013a). In both countries, it was found necessary during the initial stages of COVID-19 to reduce the hours of operation of civil amenity sites where individuals delivered their recyclable waste and ask the public to store this waste at home or rent private waste containers (ACR, 2020). Other European countries, such as Finland, diverged from some of the guidelines of the EC (2020) and instructed that waste from infected persons must be collected separately from general waste.

In the USA, the Department of Transportation (US DOT, 2019) does not classify SARS-associated coronavirus (SARS-CoV) as a 'Category A' infectious substance for humans or animals, but as a US Department of Health and Human Services select agent. 'Category A' for transportation purposes, according to the WHO (2012), is such substance(s) that 'when exposure to it occurs, is

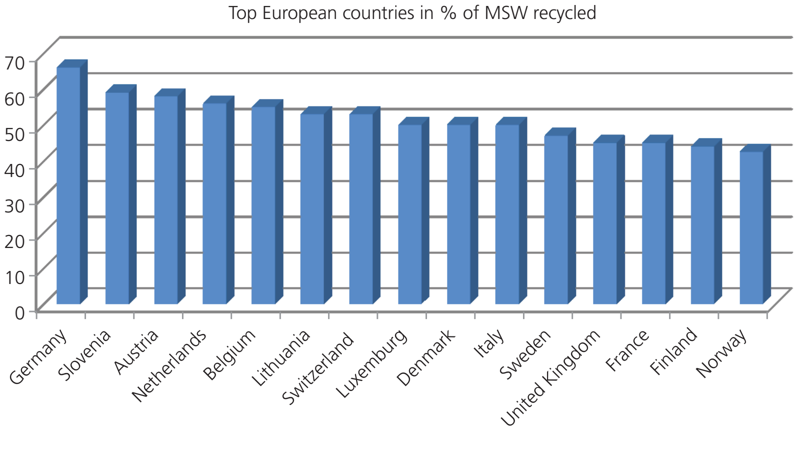

Figure 7. Eurostat 2018 data of the top 15 European countries in recycling rate of MSW

capable of causing permanent disability, life-threatening or fatal disease in otherwise healthy humans or animals', and hence is regulated as hazardous material. The US DOT and the US Centers for Disease Control and Prevention (CDC) have provided instructions to waste collectors and recyclers on shifts and space rearrangement, social distancing between employees and hygiene measures for personnel, vehicle and equipment (CDC, 2020). Both entities have ascertained that current SWM practices in the USA are adequate for protection of the health of MSWEs, and SARS-CoV-2-contaminated MSW should be managed 'like any other non-contaminated municipal waste' (ACR, 2020).

The risk of infection to employees has led supermarkets and public recycling centres in many areas in California and Massachusetts, USA, to suspend services of accepting and paying for empty bottles and cans, thus reducing plastic and aluminium recycling streams (Kaufman and Chasan, 2020). Several of these recycled items, such as old tires (Junqueira *et al*., 2006) and compressed polyethylene terephthalate bottles (Santos *et al*., 2014; Silva and Palmeira, 2019; Vieira *et al*., 2016), had been used in the construction of landfill's components and geotechnical works. Hence, interrupting recycling operations has both increased the volume of discarded items and reduced landfills' construction material.

Services in reselling or recycling discarded clothing are primarily manual, with sorting done by pulling clothes from conveyors, examining each clothing item individually and placing it in one of many sorting bags (National Geographic, 2020). The current pandemic has affected companies dealing with producing and selling textiles from second-hand clothing and shoes, reducing their operations significantly. However, some cities, such as New York and Atlanta in the USA had continued usual recycling activities. Recycling of raw material from masks (non-woven fabrics), after proper collection and disinfection, may also be considered for the creation of geosynthetics, filter cloth and dustproof geotextile. This will alleviate the problem of exorbitant waste from these items during the pandemic, which, for example, in China, is predicted to produce about 162 000 t of mask-related waste in 2020 (www.wasteinchina.com).

House-to-house collection of MSW (Botti *et al*., 2020) is the most practised method in urban areas and rural communities of many developing countries, with MSWEs being vulnerable to SARS-CoV-2 infection. In India, the number of MSWEs is estimated to lie between 1.5 and 4 million people (Bose and Bhattacharya, 2017). Waste pickers in some cities provide a door-to-door collection service, not only gathering residential waste but also separating it into recyclable fractions, which subsequently get delivered to the recycling industry, thus supplementing their income. These workers, who are indispensable for the SWM system in India, are facing the dual threat of infection and impoverishment. Their health is put at risk because of the collection of waste from asymptomatic carriers or households that do not follow the rules to segregate infected waste items and from the negligence of private waste contractors to supply them with PPE. Their financial hardship has resulted from the fact that in many cases, they are not covered by health insurance and that COVID-19 has halted many recycling operations, thus significantly reducing their income, which does not usually exceed US$170 per month (Ajwani, 2020). Several local authorities in India have stopped household collection of MSW from quarantined homes during the period of isolation to reduce the threat of infection. Thus, for example, the government of Madhya Pradesh and Andhra Pradesh, India, has advised state municipalities to cease collection from infected households. However, the lack of official guidelines and the ambiguity in the length of the quarantine period (being 14 days in some cases and 28 days in other cases) may lead to failure of this strategy to contain the spread of COVID-19.

5. Recommendations and conclusions

Waste collection is the initial stage of SWM with various systems existing, such as curbside bins, pneumatic systems and door-to-door collection. Future improvements in waste collection may include minimisation of human contact with MSW by employing automatic collection systems, such as pneumatic ones. The widespread use of airtight degradable garbage bags should be explored in biodegradable storage and sealing containers (Adamcová and Vaverková, 2014; Adamcová *et al*., 2019).

Mobile waste incineration plants, such as those recently proposed by Wajs *et al*. (2019) in Poland, may be considered for treating IMSW directly at the collection sites of quarantined areas, thus minimising the risk to MSWEs, the public and the environment. The mobility of such devices reduces the risk of spreading infectious substances during transportation, temporary storage and other chains of centralised WtE systems. Ashes from waste and sludge incineration can be used as additives to cements used in construction (Rutkowska *et al*., 2018).

The pandemic has posed a challenge to currently available sterilisation techniques, which frequently damage materials upon sterilisation. The need for effective alternatives has driven research to investigate the use of supercritical carbon dioxide ($scCO_2$) and other supercritical fluid technologies (Hrnčič *et al*., 2020; Soares *et al*., 2019). Supercritical sterilisation appears to have the potential not only to replace conventional techniques but also to prove effective for sterilisation of sensitive materials (Ribeiro *et al*., 2020).

Understanding bioaerosol generation and transport is extremely important, especially for developing countries, many of which still utilise open dumps, turning these into hotspots of environmental and public health hazards (Garcia-Alcega *et al*., 2020; Madhwal *et al*., 2020; Wei *et al*., 2019). Bioaerosols can include viruses, bacteria, fungi spores, cysts of protozoa and parasite eggs, and their release is facilitated by various activities during waste collection, loading and unloading, transportation, sorting, on-site and landfill compaction and coverage of MSW.

Although the number of pathogens found in waste can be low, depending on environmental conditions, these can survive for days in the case of bacteria, for months as regards viruses or even years in connection with helminth eggs (Breza-Boruta, 2016; Ray *et al*., 2005). Therefore, more studies are required to establish the life of viruses in anaerobic and aerobic conditions in landfills, digesters and composting sites, as well as the distances that airborne viruses can travel and remain active.

In terms of protecting MSWEs and reinforcing sanitary measures across the MSW industry in developing countries, there exists a large body of practices and guidelines from international entities, such as the ISWA and WHO; European organisations, such as the EC and the ECDC; US departments and agencies, such as the Department of Labor's OSHA, the DOT and the CDC; and Chinese ministries, agencies and organisations (e.g., Chinese Pharmaceutical Association, 2020), which provide valuable information that can be consulted and used as blueprints for improvements.

Finally, pandemic preparedness and response in the waste sector should address issues such as (*a*) assessment of disinfectant and chemical concentration levels in MSW during the COVID-19 pandemic; (*b*) effect of the disinfectants on the activities of microorganisms in the leachate and during MSW decomposition, as well as trihalomethane generation during OM degradation in various biological treatments; (*c*) characteristics of the volatile organic compounds generated during the heat treatment of IMSW; (*d*) possible utilisation of disinfected/sterilised non-biodegradable fractions of gloves, masks and protective equipment in composite construction materials; (*e*) risk assessment of all the chains of the MSW industry, identifying weak links and analysing the cost of mitigation measures, as well as the social acceptance of such interventions; and (*f*) identification of the mechanisms and factors affecting virus transport and activation in landfill barrier material, the soil and groundwater.

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