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Challenges and practices on waste management and disposal during COVID-19 pandemic

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ABSTRACT
The COVID-19 pandemic has imposed a global emergency and also has raised issues with waste management practices. This study emphasized the challenges of increased waste disposal during the COVID-19 crisis and its response practices. Data obtained from the scientific research papers, publications from the governments and multilateral organizations, and media reports were used to quantify the effect of the pandemic towards waste generation. A huge increase in the amount of used personal protective equipments (facemasks, gloves, and other protective stuffs) and wide distribution of infectious wastes from hospitals, health care facilities, and quarantined households was found. The amount of food and plastic waste also increased during the pandemic. These factors caused waste treatment facilities to be overwhelmed, forcing emergency treatment and disposals (e.g., co-disposal in a municipal solid waste incinerator, cement kilns, industrial furnaces, and deep burial) to ramp up processing capacity. This paper discussed the ways the operation of those facilities must be improved to cope with the challenge of handling medical waste, as well as working around the restrictions imposed due to COVID-19. The study also highlights the need for short, mid, and longer-term responses towards waste management during the pandemic. Furthermore, the practices discussed in this paper may provide an option for alternative approaches and development of sustainable strategies for mitigating similar pandemics in the future.

1. Introduction
Since the discovery and emergence of new coronavirus, officially called COVID-19, declared as a public health emergency of international concern (PHEIC) by the World Health Organization (WHO), various measures and preventions have been conducted by many countries (Fadare and Okoffo, 2020; Sohrabi et al., 2020). Globally, the number of confirmed cases has reached over 98 million in 219 countries and territories with an accumulated death of over 2 million as of January 21, 2021, and it is still continuously increasing (Woldometer, 2021b). Extraordinary measures including lockdown have been conducted by many countries, which have been reported as one of the most effective preventive measures. Unprecedented actions such as good manner hygiene (frequent hand washing), social distancing, school and workplace closure, travel restriction, and self-isolation have been brought up by the governments at all levels to reduce the spread of COVID-19. The WHO and other national disease control centers have issued various guidelines for the prevention of the virus. Furthermore, the emergency and the response actions also influence waste generation, management, and disposal.

The frontline medical workers (e.g., doctors, nurses, caregivers, etc.) and other people handling COVID-19 patients have been suggested to use personal protective equipment (PPE) e.g., facemasks, medical gloves, aprons, and disposable protecting cloths. In addition, their residents are also suggested to wear facemasks when going to public areas. Due to these recommendations, billions of PPE are produced and used daily during the COVID-19 pandemic. Since COVID-19 could remain feasible on the surface objects for few hours and up to several days
The rapid increase in medical wastes during the COVID-19 pandemic may disrupt medical waste treatments since they are designed for normal conditions. In Wuhan city, where the COVID-19 was firstly reported, the medical waste dramatically increased from 40 tons/day to about 240 tons/day, exceeding the medical waste treatment capacity of 49 tons/day (Tang, 2020). In Malaysia, the clinical waste increased an estimated 30% in March 2020 (Agamuthu and Barasarathi, 2020). Commonly, thermal-based technologies have been widely used to treat hazardous wastes including incineration, plasma method, microwave treatment, and steam treatment (Klemes et al., 2020). Based on the Ministry of Ecology and Environment of China, the disposal capacity of medical waste has increased by 23%, from 4903 tons/day to 6022 tons/day in China during the virus outbreak (Tang, 2020). If the estimated amount of medical wastes far exceeds the existing capacity of the treatment, new treatment facilities need to be built. However, it is not easy for increasing treatment capacity in the short time during the pandemic. As an alternative, the existing municipal solid waste (MSW) incinerators and other facilities can be utilized to ramp up the treatment capacity. For instance, the existing cement kilns are applied to treat the extra medical wastes in Wuhan city. When MSW incinerators are utilized to ramp up the capacity, the technical issue is crucial to ensure that these approaches can deal with the dynamics of the quality and quantity of the infectious wastes.

This study emphasizes the challenges of waste management and disposal during the pandemic of COVID-19. Apart from the interpretation of global COVID-19 waste generation, this paper also estimates the demand for facemask which has the potential to become infectious waste. Further, the existing and alternative disposal technologies for dealing with extra COVID-19 wastes were reported to explore the appropriate solutions. Moreover, this study also suggests some recommendations that will be useful for the community, waste management sector, government, and policymakers in designing effective waste management systems during and aftermath of similar pandemics in the future.

2. Estimation of daily facemask usage and medical waste during COVID-19 pandemic

Since the human-to-human transmission of COVID-19 has been declared, healthcare workers depend on the PPE to protect themselves and their COVID-19 patients from being infected and infecting others. Many countries have encouraged their residents to prevent coronavirus infection by wearing facemasks in public areas. This situation resulted in a significant increase in the demand for facemasks and PPE around the world. A previous study has estimated around 129 billion facemasks were required for the response of COVID-19 each month, and the global demand for gloves reached 65 billion monthly (Prata et al., 2020). Until October 20, 2020, China has supplied 17.9 billion facemasks, 1.73 billion protective clothes, 0.54 billion COVID-19 detection kit to 150 countries, and 7 international organizations, but it still cannot fully meet the huge demand of PPE in the world (Xi Jinping, 2020).

According to the total population and the percentage of urban population, the number of facemasks used daily in the world is estimated to reach over 7 billion (Table 1) (Woldometer, 2021b), which is more than the value reported by the previous study (Prata et al., 2020) due to the rapid spread of the COVID-19 virus. The detailed methodology for the estimation of daily facemask use and medical waste generation can be found in the Appendix. The Asia region has the highest number of daily facemasks users, accounting for 54% of the total daily facemasks consumption globally. This is because that the Asia region has the biggest population in the world and more countries in Asia have assigned compulsory facemask use for their citizens. Table 2 shows the estimated daily facemask use in selected Asian countries. Up to now, the COVID-19 outbreak still exists in many countries, even though serious active measures have been implemented. The health alert protocol has been strictly addressed to control virus transmission. The use of PPE such as facemasks is believed to reduce the potential of human-to-human infection, however, the discarded masks must be properly disposed of.

3. The challenges of waste management during the COVID-19 outbreak

The COVID-19 pandemic also greatly affected the quality and quantity of the generated wastes including MSW and medical wastes. Due to the lockdown implementation by the government authorities, there are potential changes in the source and volume of solid waste generation (SWANA, 2020). An increase in food waste generation during the COVID-19 crisis might be due to the limitation in storage, overcooking habits, and overbuying (Jribi et al., 2020). In both India and Singapore, a huge amount of fresh fruits and seasonal crops were wasted due to the sudden lockdown policy (Channel News Asia, 2020; FAO, 2020). During the lockdown period, most of the eating places around the world have been temporarily closed to ensure social distancing. Consequently, there is a significant increase in the demand for food delivery services and online groceries which likely caused a surge in packages such as plastics and papers. Fig. 1 shows the demand for plastics by segment. During the COVID-19 pandemic, the packaging materials (44.8%) and others (13.20%) including medical stuff are projected to increase due to the demand for PPE, food delivery service, and online groceries.

The demand for plastics in the medical sector includes face shield (Polypropylene (PP)), vinyl gloves (Polyvinylchloride (PVC)), disposable bags, tubes, masks (non-woven material, such as spun bond and

### Table 1
Estimated daily facemask use in the world with accumulated confirmed COVID-19 cases.

| Country   | Population<sup>a</sup> | COVID-19 cases<sup>b</sup> | Urban population<sup>c</sup> (%)<sup>d</sup> | Total daily facemask use (pieces)<sup>e</sup> | Discarded facemask (tons/day)<sup>f</sup> | Medical waste (tons/day)<sup>g</sup> |
|-----------|------------------------|---------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Asia      | 4,628,322,315          | 22,315,871                | 50.90%                          | 3,769,305,693                   | 11,308                          | 55,630                          |
| Africa    | 1,358,208,732          | 3,356,223                 | 43.80%                          | 951,832,679                     | 2,855                           | 8367                            |
| Europe    | 747,882,582            | 28,216,000                | 74.50%                          | 891,476,038                     | 2,674                           | 70,338                          |
| North     | 591,669,479            | 28,558,410                | 82.60%                          | 781,950,383                     | 2,346                           | 71,192                          |
| South America | 432,731,157         | 14,926,579                | 85.50%                          | 591,976,223                     | 1,776                           | 37,210                          |
| Oceania   | 42,567,863             | 49,677                    | 67.80%                          | 46,177,618                      | 139                             | 124                             |

<sup>a</sup> Data retrieved on January 21, 2021 (Woldometer, 2021b).
<sup>b</sup> The urban population was taken from (Woldometer, 2021c).
<sup>c</sup> Total daily facemask usage was estimated according to (Vizdiegyu and Chang, 2020).
<sup>d</sup> The mass of discarded facemask was calculated based on the assumption (0.3 g/facemask).
<sup>e</sup> The medical waste generation was estimated based on the study done by (Sangkhram, 2020).
melt blown spun bond) (Klemes et al., 2020; Prata et al., 2020). The huge demand for delivery services and online groceries may increase the common packaging materials such as Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), Polypropylene (PP), Polyethylene Terephthalate (PET), Polystyrene (PS), etc (Fig. 1). Unfortunately, the recycling activities of plastic wastes have been reduced due to the COVID-19 pandemic, resulting in a great challenge in plastic wastes management (Tenenbaum, 2020). Even though this surge is unavoidable, the environmental protection approaches should be taken into account during and after the COVID-19 pandemic (Klemes et al., 2020; Patrício Silva et al., 2020). Particularly, the fully developed plastic waste management strategies are required to assist the system design, footprints, and comparison alternatives. The concept of Plastic Waste Footprint (PWF) can be introduced to capture the environmental burdens of plastic products throughout their life cycle (Klemes et al., 2020).

Many infectious wastes are produced during the COVID-19 pandemic. The source of contaminated wastes is not only produced from the health facilities including hospitals and temporal medical facilities but also generated by household and quarantine center facilities. Home isolation has been used for patients with mild symptoms or travelers for at least 14 days. So that hospitals can be prioritized for severe case patient who needs intensive medical treatment. This approach is believed to control the COVID-19 outbreak, however, it may present new and crucial challenges for waste management and treatment. It is indicated that wastes resulting from households and quarantine facilities with suspected or positive COVID-19 cases may contain viable COVID-19 virus and possibly be a source of infection. Fig. 2 summarizes the potential source of contaminated waste during the COVID-19 pandemic.

Table 2
Estimated daily facemask use in selected Asian countries with accumulated confirmed COVID-19 case.

| Country       | Population ( millions ) | COVID-19 cases | Urban population (%) | Total daily facemask use (pieces) | Discarded facemask (tons/day) | Medical waste (tons/day) |
|---------------|-------------------------|----------------|----------------------|-----------------------------------|------------------------------|-------------------------|
| China         | 1,439,323,776           | 88,701         | 61%                  | 1,404,780,005                     | 4,214                        | 221.119                 |
| India         | 1,387,530,727           | 10,611,719     | 35%                  | 777,017,207                       | 2,331                        | 26,453.500              |
| Indonesia     | 275,127,290             | 951,651        | 56%                  | 246,514,052                       | 740                          | 2,372.330               |
| Pakistan      | 223,256,147             | 527,146        | 35%                  | 125,023,442                       | 375                          | 1,314.100               |
| Bangladesh    | 165,599,479             | 530,271        | 39%                  | 103,334,075                       | 310                          | 1,321.890               |
| Japan         | 126,259,973             | 339,774        | 92%                  | 185,854,680                       | 558                          | 847.008                 |
| Philippines   | 110,388,276             | 507,717        | 47%                  | 83,011,984                        | 249                          | 1,265.666               |
| Vietnam       | 97,824,681              | 1546           | 47%                  | 59,477,406                        | 178                          | 3.854                   |
| Turkey        | 84,842,191              | 2,406,216      | 76%                  | 103,168,104                       | 310                          | 5,998.353               |
| Iran          | 84,588,146              | 1,354,520      | 76%                  | 102,859,186                       | 309                          | 3,376.625               |
| Thailand      | 69,897,587              | 12,795         | 51%                  | 57,036,431                        | 171                          | 31.896                  |
| Myanmar       | 54,612,547              | 135,721        | 31%                  | 27,087,823                        | 81                           | 338.333                 |
| S. Korea      | 51,293,799              | 73,918         | 82%                  | 67,207,464                        | 202                          | 184.267                 |
| Iraq          | 40,718,860              | 611,407        | 73%                  | 47,559,628                        | 143                          | 1,524.150               |
| Afghanistan   | 39,410,451              | 54,483         | 25%                  | 15,764,180                        | 47                           | 135.818                 |
| Saudi Arabia  | 35,113,472              | 365,775        | 84%                  | 47,192,506                        | 142                          | 911.825                 |
| Uzbekistan    | 33,737,441              | 78,219         | 50%                  | 26,989,953                        | 81                           | 194.989                 |
| Malaysia      | 32,595,582              | 172,549        | 78%                  | 40,679,286                        | 122                          | 430.140                 |
| Yemen         | 30,187,320              | 2115           | 38%                  | 18,353,891                        | 55                           | 5.272                   |
| Nepal         | 29,425,912              | 268,646        | 21%                  | 9,887,106                         | 30                           | 669.696                 |
| Taiwan        | 23,840,809              | 872            | 79%                  | 30,134,783                        | 90                           | 2.174                   |
| Sri Lanka     | 21,463,233              | 55,189         | 18%                  | 6,181,411                         | 19                           | 137.578                 |
| Kazakhstan    | 18,901,121              | 172,412        | 58%                  | 17,540,240                        | 52.62                        | 429.798                 |
| Syria         | 17,734,143              | 13,313         | 60%                  | 17,024,777                        | 51.07                        | 33.187                  |
| Cambodia      | 16,846,976              | 453            | 24%                  | 6,469,239                         | 19.41                        | 1.129                   |

* a The urban population in Asian countries was taken from (Woldometer, 2021a) (Woldometer, 2021c).

b The mass of discarded facemask was calculated based on the assumption (3 g/facemask).

c The medical waste generation was estimated based on the study done by (Sangkham, 2020).

Fig. 1. Plastic wastes by segment (Geyer et al., 2017), which are expected to increase in trend of medical and packaging wastes.
COVID-19 cases are suggested to limit the use of separate waste collection systems. Consequently, it increases the generation of mixed wastes. However, the implementation of the proposed waste management practice is still challenging, not simple, and needs excellent coordination among health authorities and the waste service sectors. In most developing countries, solid wastes including MSW are discharged in open dumping or in unsanitary landfills where waste scavengers without wearing personal protective tools are working for collecting recyclable materials (Nzediegwu and Chang, 2020). Besides, it is well-known that poorly managed landfills are recognized as a “food source” for livestock e.g., cows, goats, and dogs which may increase the spread of diseases including COVID-19. Inadequate decontamination and disposal of plastic bottles used for packaging drinks in healthcare and quarantine facilities may be another potential source of virus transmission in developing countries.

As discussed above, the challenges in waste management during the pandemic includes 1) a sudden significant increase in medical and infectious wastes from hospitals and households, while the capacity in existing treatment facilities cannot fulfill the new requirement, 2) the generation and composition of MSW are also varied with the presence of more food wastes and plastics, and 3) the risk of virus transmission by infectious waste is high in a rural area or in developing countries.

4. Immediate responses on waste management and disposal during the COVID-19 pandemic

4.1. Current disposal of waste during the COVID-19 pandemic

As mentioned earlier, hospitals, healthcare facilities, designed quarantine centers, and households are producing more infectious wastes including discharged PPE. The wastes produced during medical care undertook at homes are also classified as such wastes, e.g., contaminated and non-contaminated PPEs, expired discharged medicines, injection needles, and other healthcare-related wastes. Household wastes may get contaminated which also diminishes the opportunity for recovery and recycling of non-hazardous waste from households. Non-segregation will increase the amount of hazardous wastes. The proper management and disposal of medical wastes and contaminated wastes are crucial to stop the further spread of coronavirus.

Sanitary landfills, incinerators and autoclaves are commonly used to treat medical wastes during the pre-pandemic (Windfield and Brooks, 2015). Other alternatives such as MSW incinerators, industrial furnaces, and cement kilns could also be employed if the existing medical waste treatment plants are overloaded. This option can be applied during this COVID-19 pandemic due to the surge in medical and contaminated household wastes, as most of the medical waste treatment facilities are designed for normal or steady-state conditions. Different incineration facilities, receiving conventional waste materials, will easily destroy the COVID-19 virus in combustion. But there can be health risks for the workers of the plants when the plants are not designed for receiving, storing, and feeding infectious waste. This has to be taken into account in the operation arrangements during pandemic waste treatment.

In Spain, it is recommended that cement plants can co-incinerate wastes upon request (ACRPlus, 2020). Norway’s government has permitted a temporary change in landfill permits and allowed to transport wastes elsewhere to deal with the medical waste surge, if necessary (ACRPlus, 2020). In China, MSW incinerators have been used for the emergency treatment of medical wastes during the COVID-19 pandemic (Ma et al., 2020). It is stated that by establishing six-layer barriers including “diversion, disinfection, reinforced packaging, feeding system improvement, negative pressure, and sanitation protection”, the infectious risks during the disposal process can be effectively avoided. In Finland, it has been instructed that the waste transportation workers should avoid working near the open doors of waste bunkers in waste incineration plants when emptying the truck especially if the crusher is in operation (Ministry of Social Affairs and Health of Finland, 2020). Moreover, the selection and use of PPE should consider the provision of the work, work environment, and employees (Finish Institute of Occupational Health of Finland, 2020).

WHO suggested that the disposal procedures and waste treatment of healthcare wastes should consider the controlled operating conditions of thermal treatment or use biocidal agents to destroy any pathogens (Kampf et al., 2020). If steam sterilization is applied for waste treatment, the operating temperature must be maintained in the range of 121 °C–134 °C in an autoclave to ensure adequate decontamination. Meanwhile, the temperature in the incinerator is controlled in the range of 850 °C to 1100 °C and sufficient residence time to ensure that the combustibles and toxic substances are completely decomposed (WHO, 2017). Germany requires strict procedures for controlling the incinerator temperature, to be at 1000 °C to ensure safe disposal (ACRPlus, 2020). For now, implementing any of these technologies are linked to the capability and adaptability of each country including the treatment cost and health and environmental risk. The approach of the technologies for COVID-19 contaminated waste are summarized in Table 3 (UNEP, 2020). The following technologies have been proposed by United Nation Environment Programme (UNEP).

4.2. Guideline for COVID-19 wastes issued by different agencies and countries

The COVID-19 pandemic has attracted much attention from many countries and agencies to respond to the solid waste management trends.
The technological approaches for the treatment of COVID-19 contaminated waste.

| Criteria                          | Preferred technologies                                      | Secondary preferred technologies                           | Emergency solutions               |
|-----------------------------------|-------------------------------------------------------------|------------------------------------------------------------|-----------------------------------|
|                                   | Autoclave/steam sterilization                               | Twin chamber incineration                                   | Barrel incinerators with air induction | Onsite pit burial               |
| **Condition**                     | Static or mobile                                           | Static or mobile                                           | Mobile                            | Static                         |
| Cost                              | Low                                                         | Medium                                                    | Low                               | Low                             |
| Scale of technology               | 200-10,000 L/cycle                                         | 50-2000 kg/h                                              | 8-25 kg/h                         | 5-10 tons of waste             |
| Suitable for/ type of waste       | Soiled wastes, bedding and PPE, clinical laboratory waste   | Soiled wastes, PPE, human anatomical wastes, chemical waste | Soiled wastes, PPE, chemical and laboratory wastes | Soiled wastes, PPE, Clinical laboratory waste |
|                                  | reusable instruments, waste sharps, glassware              | laboratory waste                                          |                                   | Disposable instruments         |
| Pollution control                 | Reduced air pollution                                      | Acceptable emissions and 90% volume reduction              | Air induction cyclonic system      | No emission                    |
|                                  | Negligible to no air emissions                              | Secondary combustion chamber, temperature controls and air pollution control equipment |                                   |                                 |
| Time of scale                     | 30-60 min per cycle, 121–134 °C                            | 6-h cycles with 1–3 batches of waste                      | 6-h cycles with multiple batches of waste |                                 |
|                                  | 30–250 kg/h in cycles of 30–60 min                         | High temperature (>-850 °C) Mandatory training             | High temperature (>650 °C) Use operating manual |                                 |
| Complexity                        | Simple                                                      | Simple                                                    | Simple                            | Layers of waste with daily soil cover until full |
| Weakness/ drawbacks               | No volume reduction                                         | Higher capital and operational costs                      | Short life span (3–5 years)       | Potential for leachate and releases to water and land |
|                                  | Odor generation, remained waste, need regular maintenance  | Poor emissions if the equipment is low quality Potential of formation and release of PCDD/PCDF | Initial incineration will produce black smoke due to the fuel source Potential of formation and release of PCDD/PCDF | The poor feedstock may lead to poor emissions |
| Application tips                  | Pair it with the shredding of material for volume reduction | Have a cool down cycle to enable safe ash removal          | Use good design quality material to build a safe model. Operate well to maintain acceptable emissions. Avoid overloading Have a cool down cycle to enable safe ash removal Fly ash easily removed | Temporal back-up technology to ease overburden of waste materials Suitable for remote sites Have a cool-down cycle to enable safe ash removal Never conduct open burning |
|                                  | Use a HEPA filter to avoid toxic contaminants release       | Encapsulate hazardous ash waste Make sure emissions controls are in place | Secure the site from waste pickers Site away from water abstraction points, waterways, crops and communities Use gauze cover to avoid vermin and odors | |
|                                  | Re-bag reduced waste volumes before sending them to landfill |                                                                           |                                   |                                 |

and practices, as summarized in Table 4. The management guidelines have been updated and modified to deal with COVID-19 contaminated wastes.

5. Proposed practices of COVID-19 wastes management and disposal

Many countries have existing rules and procedures for the disposal of medical wastes from hospitals and households. Some adjustments to the waste management practice have been made during the COVID-19 pandemic period. The solid waste management trends and practices are illustrated in Fig. 3.

5.1. Waste generation, handling, and storage

As described above, the restricted movement order and lockdown policy have affected the generation of wastes including medical wastes and MSW. The medical wastes generated in hospitals and health care facilities are aligned with the number of infected patients. These wastes are handled as common medical waste followed by the procedure practiced in general hospitals. However, it is suggested that COVID-19 related medical wastes should be packaged with double-layer medical waste bags and labeled as “COVID-19 infection” (Peng et al., 2020). The surface of bags should be decontaminated by spraying chlorine-containing disinfectants before placing them into a medical container (Wang et al., 2020). The generated waste from the infected homes should be double-layer packaged and sealed before storing them in collection bins.

The total lockdown has increased the generation of household food wastes and single-use plastics including plastic-based PPEs and packaging materials. In a typical household with COVID-19 infection, all wastes should be treated as non-recycled wastes since the recycling activities should be avoided to prevent the potential infection from wastes. In developed countries, recycling waste is well-managed and standardized by formal sectors including government or specialized enterprises. However, in most developing countries that have relatively low- or middle-income and no strict regulations, the waste recycling activity is done by both formal and informal sectors. The informal
Table 4 Guidelines for COVID-19 contaminated wastes by different agencies and countries.

| Country/Agency       | Guideline for waste management during COVID-19 pandemic |
|----------------------|-------------------------------------------------------|
| WHO (WHO, 2020)      | WHO has issued guidelines for the disposal of infectious and non-infectious healthcare wastes during COVID-19 crisis. The COVID-19 waste should be safely collected and disposed of. All workers involved in waste management and disposal must be equipped with proper PPE. |
| US EPA (US EPA, 2020) | The United States Environmental Protection Agency (US EPA) responded by releasing guidelines for recycling and sustainable management of food wastes during the COVID-19 outbreak. These guidelines include food waste management at households, institutions, and business levels. |
| United States (OSHA, 2020) | The U.S Occupational Safety and Health Administration (OSHA) has defined the safety guidelines for personnel workers involved in MSW management. Strict engineering and administrative controls, safe work practices, and proper PPE (gloves, gowns, masks, and face shields) should be applied to protect workers from exposure to contaminated recyclable materials. |
| SWANA (SWANA, 2020) | The Solid Waste Association of North America (SWANA) reminds all stakeholders, including the nation’s governors, mayors, elected officials, and leaders that solid waste collection, processing, and disposal are a crucial public service and should be issued from local or state-wide quarantines in response to the COVID-19 pandemic. |
| Europe (European Commission, 2020) | European Commission has issued guidance for waste management during the COVID-19 crisis to ensure a high level of protection of human health and the environment. The guidance involves preventing or reducing distortions in waste management services, dealing with an increasing amount of medical wastes, ensuring enhanced health and safety at work, and providing safe handling of household wastes generated from residents with confirmed cases. |
| United Kingdom (DEFRA, 2020) | The British government has formulated COVID-19 regulatory position statements for local authorities and waste collectors. These guidelines focus on waste stream prioritization, expansion in the temporal waste capacity, waste segregation, an adaptation of MSW incinerators to dispose of COVID-19 infectious waste, and communication with residents. |
| India (CPCB, 2020) | The COVID-19 related wastes should be carefully treated such as double-layered bags, COVID-19 labeled, and independently stored. The labeling is to ensure the priority treatment and disposal immediately upon at Common Bio-Medical Waste Treatment Facilities (CBWTF). The quarantine facilities and urban local bodies should engage CBWTF, thus the collection and disposal at their facilities can be timely ensured. The workers involved in COVID-19 waste management should be equipped with appropriate PPE. Also, the dedicated vehicle used for the COVID-19 waste collection should be labeled. |
| China (MEE of China, 2020) | The Ministry of Ecology and Environment of the People’s Republic of China issued ‘COVID-19 Infected Pneumonia Medical Waste Emergency Disposal Management and Technical Guide’. The infectious medical wastes generated during the COVID-19 pandemic should be strictly packaged according to the standards for special packaging bags, containers, and warning signs for medical wastes. Medical waste disposal units (e.g., hazardous waste incineration plants, domestic waste incineration plants, industrial furnaces, and other emergency sectors may face some problems in terms of their health and livings by enforcing of lockdown and economies slow down. Thus, the best management practices play an important role in handling such waste and mitigating waste worker’s exposure to infectious wastes. The food waste and its packaging material from suspected or confirmed COVID-19 patients should be carefully handled, such as stored in double layers and biodegradable bags. The PPE and other self-health care products should be treated as hazardous or infectious wastes that need to be kept in double-lined sealed bags with a specific COVID-19 symbol. |

5.2. Waste collection and transportation

Due to the social distancing, lockdown, and restriction of exit-entry across the borders of cities or provinces, the daily activities are disrupted, and this influenced the scheduled waste collection. The collection frequency should be increased to meet the requirement. COVID-19 wastes collection should be arranged by well-trained staff and special vehicles. Safe transportation needs vehicles that can be sterilized, trained waste pickers and drivers, dedicated routes, and equipped with waste tracking systems (ADB, 2020). Specific training must be delivered for staff that will be exposed to COVID-19 waste. The route and time of transportation should avoid overcrowd and rush hour period. The storage space and vehicles should be disinfected immediately after loading and unloading (Sharma et al., 2020). suggested that the collection frequency of biodegradable waste can be adjusted according to the waste amount in the region, while the collection frequency of recyclable waste can be reduced according to the availability of transportation units. It is due to a surge of food wastes from households during the lockdown. The citizen can be encouraged to store the recyclable waste in double-sealed bags for longer periods. A delay in waste collection time of 72 h is also suggested by the Association of Cities and Regions for Sustainable Resource Management (ACRPlus, 2020). On the other hand, more waste trucks may be required and collection frequency should be increased to collect the COVID-19 wastes from hospitals, health care facilities, and quarantine homes. A dedicated hazardous waste collection schedule from homes needs to be established to avoid mixing MSW with contaminated wastes, as is being done in Korea (Rhee, 2020).

5.3. Waste treatment or final disposal

As the easiest method for the centralized destruction of pathogens, incineration can be prioritized for treating all infectious wastes. A high temperature of the incineration process can not only destroy the pathogens but also incinerate the organic materials and convert them into inorganic substances. The mass and volume of waste can be reduced by approximately 85–90% (Wang et al., 2020). For the incineration of hazardous waste, the produced ash is suggested to be disposed of in a special landfill. If the hazardous waste incinerator achieves the
maximum capacity, co-disposal of COVID-19 related wastes with MSW can be done in the MSW incinerator. However, technical modification such as the improved design of the feeding may be required. On the other hand, the area with limited centralized treatment facilities or no thermal treatment facilities should adopt deep burial of COVID-19 wastes in secured landfills. Direct handling of contaminated wastes in the COVID-19 spots should be completed by skilled and protected workers. Local governments should monitor and advise their citizens to take responsibility. The recycling work should be reduced by doing proper home segregation and always follow the update of guidelines for handling COVID-19 wastes. The awareness of the people in waste management during the pandemic must be strengthened by intensifying good communications and awareness campaigns.

One important issue in developing countries where most of the wastes are disposed of in unsanitary landfill or dumpsite, the activity of scavengers or informal waste pickers must be strictly controlled. The unsegregated wastes will need longer time for manual sorting in the dumpsite, resulting in the longer and wider exposure of waste pickers with contaminated wastes. Therefore, the chances of transmission of pathogens such as COVID-19 virus will be higher if they are not well protected. The emergency burial pit can be used in developing or lower-income countries with a lack of access to medical waste treatment facilities during the COVID-19 pandemic. Safe onsite burial is feasible for relatively limited periods (e.g., 1-2 years) and small quantities of wastes (i.e., 5-10 tons in total), and the detail is described by WHO (WHO, 2015). Briefly, the collected waste is buried in a close pit (2 × 5 m) with a clay layer or geosynthetic lining at the bottom. After putting wastes into the pit, fresh soil or solid-lime mixture shall be filled for covering. The top layer of the pit should be covered by cement or embedded with wire meshes. Afterward, 50 cm of soil should be covered above the wire mesh embedded. The pit areas should be isolated from human activities and animals by installing wire barriers. A safe onsite burial can be prepared in the existing dumpsite, and can also be considered during the COVID-19 pandemic when incinerators have reached the maximum capacity.

5.4. Short term, and mid-and longer-term responses

In the first period of the virus outbreak, the management and treatment of COVID-19 related waste are gaining much attention and challenge. During the pandemic, there was a sudden surge in COVID-19 waste amount from the medical facilities and quarantined homes. A strict and timely collection, treatment, and disposal with fully safe measures play a crucial role in the handling of COVID-19 waste. In this regards, several responses to COVID-19 waste management are summarized as follows:

5.4.1. Short term responses

1) Any wastes that have been contacted with the facilities which were used for housing COVID-19 patients should be treated as medical wastes using hazardous waste treatment technologies.

2) The COVID-19 wastes can be disposed of via incineration, autoclave, or special landfill. If their facilities begin to be overwhelmed, cement kilns, industrial furnace, MSW incinerator may be utilized as temporary disposal facilities for COVID-19 wastes.

3) Due to surge quantities of contaminated wastes, it is suggested to use contemporary stockpiling of conventional hazardous wastes.
which have been paved and equipped with wastewater collection before being incinerated. The temporary stockpile may be also a better option before comprehensive solutions such as disinfection, material recycling, and recovery and final disposal will be available in the country.

4) The awareness campaigns on the source segregation of wastes need to be strengthened by clear communication and strong encouragement. Whenever possible, training and guidance should be delivered to the citizens.

5) Provide practical guidelines for consumers and citizens on how to reduce single-use products (single used plastics) consumption, and educate on sustainable approaches and best disposal alternatives.

6) The waste management workers including sanitation workers need to be protected by providing PPE and regular health monitoring. The government should actively pay more attention to the informal workers who are participating in the collection and transport chain. The informal works lack access to PPE and healthcare facilities.

7) The continuation of waste collection needs to be ensured during the pandemic including waste tracking and labeling. Readjustment of the schedule may be needed, if necessary.

8) The additional waste vehicles should have a loading area that is non-absorbent, sealed, and capable of being locked and disinfected, and it must be separated from the driver’s cabin. The vehicle’s identification number should be recorded and well documented for future control.

9) The emergency safe disposal method e.g., deep burial should be made immediately based on WHO’s guidelines, especially in developing countries.

10) Recycling activities in households having infected people and manual sorting and picking in waste treatment plants and landfills should be avoided during the pandemic to prevent human contact with any infectious wastes including MSW and medical wastes.

11) The local government, specialized enterprises, and community should actively consolidate in waste management practices during and after the pandemic.

5.4.2. Mid-longer term responses

1) The existing MSW management system needs to be appropriately organized and prepared to handle household medical waste such as clear labeling and special bins. The disposal fee of hazardous wastes to be incinerated should be ensured by considering the region, capacity, and waste characteristics.

2) Basic infrastructure establishment and capacity improvement of the new proposed design of medical contaminated waste treatment are urgently needed and should be developed to overcome a similar crisis or disease outbreak.

3) Sustainability Assessment of Technologies (SAT) for Best Available Technology (BAT) by considering technical, social, economic, and environmental performances should be promoted. The treatment approaches can be more flexible (various feedstock), decentralized, and advanced (such as Internet-based).

4) Financial resources and mechanisms for improving the infrastructure and guidance on creating and accessing funding should be clearly identified to support the countries.

5) Revision of the existing policy and regulation to make citizens a more responsive and institutional basis shall be considered to better respond to a similar future situation and to clarify the actions to be taken.

6) Awareness and enrichment of the skills and knowledge on the positive impact of the proper management of hazardous or infectious wastes shall be enhanced.

6. Conclusions and future outlook

Improper waste management during the COVID-19 pandemic carries potential risks to the waste handling personnel and increases virus transmission. Therefore, strict procedures and guidelines of COVID-19 wastes should be carefully followed to reduce the risk of the virus spreading to the environment among the medical facilities, communities, and public areas. The unprecedented surge in medical waste and other infectious waste from homes also require more attention. The challenges in waste management and its immediate responses to the current COVID-19 crisis are reviewed. Finally, short term responses and mid-longer term responses are given in the context of waste management during and after the pandemic.

It is worth to mentioning that the COVID-19 pandemic give a remarkable impact on the existing solid waste management practices. More plastic or paper packages and food wastes have been found in waste caused by the lockdown period. COVID-19 wastes should be managed and treated whenever possible using existing protocols for infectious and healthcare waste management, as suggested in national or international guidelines. The waste collection should be carefully handled by a fully protected waste workers, and the waste tracking and labeling need to be ensured. The waste vehicle should be identified and fully recorded. With proper waste management and practices in existing treatment and disposal such as decentralized waste management and its integration, the adverse impacts can be minimized. When the treatment facilities lack of capacity, co-disposal of COVID-19 waste can be done in the existing thermal treatment such as MSW incinerator and cement kilns, or deep burial can be applied in existing dumpsite as an emergency treatment. This study provides basic knowledge for further research in sustainable waste management during the pandemic. Furthermore, the information discussed herein will greatly facilitate the approach developed for dealing with similar possible pandemics in the future.

Credit Author Statement

Dwi Hantoko: Conceptualization, Data Curation, Writing - Original Draft. Xiaodong Li: Writing - Review & Editing, Investigation, Validation. Agamuthu Paritamby: Writing - Review & Editing, Investigation, Formal Analysis. Kunio Yoshikawa: Writing - Review & Editing, Data Curation, Validation. Mika Horttanainen: Writing - Review & Editing, Methodology, Investigation. Mi Yan*: Writing - Review & Editing, Visualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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