Biological Waste Management for COVID-19 and Future Pandemics: A Holistic Framework

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Abstract

The aim of this paper is concerned with evaluating and assessing the COVID-19 waste management plan to develop a generalized waste management framework that can be adopted with future pandemics based on the UAE approach. Some existing models for waste management across different countries across the globe and the extent to which they could be applied in defined areas are discussed. An integrated framework that can serve as a basis for the development of a waste management system is proposed. Applicability, benefits, challenges, and limitations of the system are all outlined with a narrower scope focusing on the different approaches adopted by several Emirates in the UAE. An in-depth analysis of the current waste management methods, as well as the focus on disposing of medical waste contaminated with COVID-19. A comprehensive COVID-19 UAE-based framework is proposed alongside a generalized framework that can be implemented in future pandemics that are associated with a pathogen carrier.

Keywords
Waste management, Disinfection, Biomedical waste, Generalized framework, and Disposal treatment technique.

1. Introduction
In late 2019, a highly contagious virus spread widely around the globe with an alarming infectious capability, resulting in the Coronavirus (SARS- CoV- 2 or COVID-19) pandemic. Since then, several challenges have been raised by the COVID-19 Pandemic, in various aspects of social life, economic status, and environmental balance (McNeely 2021). In particular, it contributed to an accelerated generation of biological waste. As of 4th November 2022, 628,694,934 confirmed cases of COVID-19 have been reported worldwide, with nearly 6,576,088 deaths, according to the World Health Organization (W.H.O. 2022). As a response to control the spread, governments and authorities worldwide imposed measures like social distancing, usage of personal protective equipment, screening facilities, isolation and caring wards, and vaccination centers.

An enormous amount of medical waste is believed to have been produced from these activities. However, the quantification of the amount of waste produced globally has been a rigorous task, as disparities exist in the manner of production and recording. Nevertheless, all reported data unanimously agree with the significant increase in the quantity of waste produced since the start of the pandemic and the high risk of infection arising from them if not handled properly. 3.4 kg/bed/day of hazardous biomedical waste was found to be generated in a survey of five Asian cities, as per an assessment by the United Nations Development Programme (UNDP), which is a significant increase from the average quantity of healthcare waste produced before 2020, i.e., 0.5 kg/bed/day (U.N.E.P 2022). In another study conducted by Sangkham et al. it was seen that a total of 16,659.48 tons/day of clinical waste was generated in Asia alone (Sangkham 2020). Rajak et al. illustrated that over 32,996 mt of the biomedical waste directly related to COVID-19 was generated in just 6 months- June- December2020 (Rajak et al. 2022). South Korea is belied to have produced over 2000 tons of medical waste until May 2020 since the pandemic (U.N.E.S.C.A.P 2022) (Ilyas 2020). It is believed that the volume of clinical waste rose by 350–500% dueto the pandemic leading to challenges in the waste disposal and management capacity of countries around the globe (Fadaei 2021).

1.1 Objectives
The objectives of this research are to:

1. Identify the current production of biological waste and its types.
2. Develop a waste management plan for the disposal of different types of identified biological waste during the pandemic.
3. Extend the developed waste management plan to accommodate future pandemics.

Increased biohazards induce biological waste productivity. Therefore, the objectives of this study are to identify the risks and effects of biological waste, analyze current control methods and implement a proposed solution to decrease the biological waste hazardous effects. It is important to safeguard the regulations and safety laws of the workers, especially in the usage and disposal of PPEs, which includes face masks, hand gloves, gowns, etc., which will assist in the control of biological waste generated from diseases such as asthma and COVID-19 (Tripathi et al. 2020). By observing these protocols, it will be possible to protect public health and control biohazard exposure.

2. Literature Review

2.1 Insights into Biological Waste

The term "biohazardous agent" is used to describe a substance that is biological in origin, has the potential to self-replicate, and is harmful to living things. Allergens, recombinant products, cultured human and animal cells and the potentially biohazardous agents these cells may contain, infected clinical specimens, tissue from experimental animals, plant viruses, bacteria, and fungi, toxins, and other biohazardous agents as defined by State and Federal regulations are all examples of biohazardous agents. Consequently, any substance that is biohazardous, either because it contains or has been polluted by a biological agent, is considered "biological waste". Figure 1 lists some examples of biological wastes (Purdue University 2019).

Figure 1. Examples of biological wastes Biological waste can be grouped into three main categories (MIT EHS 2019):

1. **Liquid waste:** Liquid waste includes any liquids that constitute or have come into contact with living biological matter, such as cultures and supernatants. In order to effectively disinfect liquid waste, the proper chemical disinfectant must be applied at a specific concentration, and the waste must remain in contact with the disinfectant for a predetermined period of time before being discarded.

2. **Solid waste (non-sharp):** Solid biological waste refers to anything that is not liquid, not sharp, and that has either been utilized with biological material or came into contact with biological material. Plastic pipettes, pipette tips, petri dishes, paper towels, and gloves are just a few examples.

3. **Sharp waste:** Sharp wastes are materials or medical equipment contaminated with biological materials that can cut, penetrate, or wear away the skin. A few examples are syringes, needles, blades, and pieces of glass from glass slides or vials.

Figure 2 describes the disposal of each of the types of biological wastes discussed above (MIT EHS 2019).

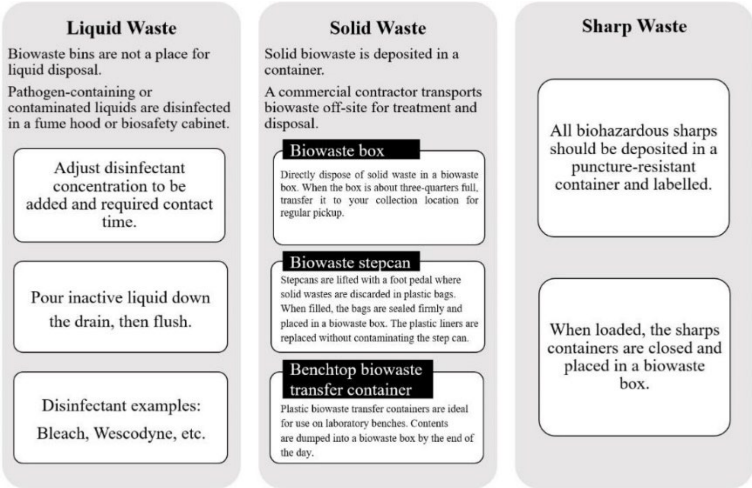

Figure 2. Disposal of different types of biological wastes

2.2 Waste Treatment Techniques

Several waste management techniques have been adopted by different countries to handle COVID-19 waste. Some of these techniques include incineration, steaming, thermal, and microwave. The selection process of the appropriate disposal techniques depends on several factors, such as quantity, cost, and waste type (Moharir et al. 2019). For instance, some facilities with high-volume waste preferred to use the incineration technique. While it was found that in small-scale hospitals and facilities with limited funds, a combination of the steam technique alongside the microwave technique has been used (Singh et al. 2022). Furthermore, during the pandemic, techniques that use thermal energy and heat have been relied on heavily for the safe disposal of contaminated waste with the Sars virus to avoid the spread of the disease. As was reported by several works of literature, the discarded material and waste produced by COVID is considered hazardous waste as it poses a potential threat to the workers to whom they are exposed to the virus.

The incineration technique uses a thermal method that involves an oxidation reaction of burned waste at high-temperature combustion that ranges between 800 °C to 1200 °C (Moharir et al. 2019). This technique has been intensively used throughout the pandemic as it has proven that it kills pathogens, viruses, and organic material (Ilyas et al. 2020). A study conducted by researchers in India has revealed that most of the COVID waste has been burned up in incineration at a temperature that is higher than 1100°C. In cases where the volume of the waste is higher, the incarnation technique is done twice with fresh charges to ensure all contaminates are burned up through the process (Jharkhad State Pollution Control Board 2022). Furthermore, The researchers of this study have highlighted the importance of having a gas treatment technique alongside incineration as the burning process produces highly toxic gases that can build up in the fatty tissue exposing workers to a risk of immune and respiratory diseases.

Thermal technology has been one of the most commonly used techniques throughout the course of this pandemic. Similarto the incineration technique, heat is also used to treat waste; however, the major difference between the two techniques isthat in thermal heat is used to physically separate the contaminants from solid waste, whilst in incineration, it is used to destroy and kill those contaminates. There are two sub-techniques underneath the thermal approach, which are: High temperature pyrolysis technique and Medium temperature microwave technique.

The pyrolysis technique burns up the waste using a pyrolysis oxidation reaction at a temperature that reneges between 540-830. The pyrolysis-oxidation, plasma pyrolysis, induction-based pyrolysis, and laser-based pyrolysis are all used up through this process. The combustion temperature vaporizes the liquid waste separating it from the solid waste. The second step of this combustion process involves combusting gasses at higher temperatures (Czajczyńska et al. 2017).

Microwave is one of the techniques that break down organic matter through the use of microwaves with high energy in a reverse polymerization process at a temperature that ranges from 177 ◦C to 540 ◦C. In this technique, the inner energy is raised due to high electromagnetic absorption, which is caused by the collision and the friction forces between the molecules. The combustion of oxygen is prevented by adding nitrogen to the inert champers. This step ensures that the atmospheric environment will have less harmful emissions caused by this technique and hence giving an advantage over the other techniques in terms of less dangerous environmental emissions. Furthermore, some of the key benefits of this technique over the others are that alongside reduced toxic emission of gases and less accumulation post the process, it also proved itself to have less heat loss and low temperature and energy. A recent study conducted in China has concluded that the built microwave devices have successfully inactivated COVID-19 by killing hydrophilic viruses. The results show promising results in terms of disinfecting COVID waste (Zhao et al. 2022).

2.3 Former Frameworks in Literature

After the COVID-19 pandemic, governments have realized the impact of biological waste on human life, the environment, and even the economic sector. Biological waste increment, especially medical waste, was followed by uncontrolled disposal/ incineration, open burning, and public health risks, which in turn, caused the release of toxins to the environment and secondary transmission of diseases to humans (UNEP 2022). Those methods were performed randomly, regardless of the WHO guidelines on the treatment of infectious and sharp waste from healthcare facilities.

Therefore, governments encouraged research organizations to establish innovative solutions to overcome this pandemic. After releasing the generally recommended regulations from WHO and The United Nations Environment Programme handbook to minimize immediate risks of biological hazards, Stop-gap solutions. Many researchers established frameworks to minimize physical interaction while generating and collecting biological waste, whereas others developed new recycling ways to decrease the pollution generated from the existing disposable methods. For example, some countries controlled medical waste by benefiting from the available facilities for waste management solutions to avoid secondary health impacts and implementing the 3S methodology (Sorting, Segregation, and Storage) (UNEP 2022). In Wuhan, China, during COVID-19, the local waste management authority developed mobile incinerators to safely dispose of contaminated single-use protective PPE, using the Internet of Things (IoT) technology in cooperation with sensing and scanning devices, location system, video surveillance and Internet access with each device (Singh et al. 2020).

On the other hand, many other developed countries, like Australia, did not have a national law or regulation on medical waste. However, after COVID-19, they followed the National Waste Policy, which specifies the general policies and strategies on waste. One of the most important policies was to label 'COVID-19 Waste' on COVID-19 waste bins and use double-layered bags for medical waste collection. Yet, each state has its own waste management regulations. Then, they developed a five steps method that included the Generation of biological waste, while considering the facility's type and size, number of treated patients, and type of treatment received. Then followed the collection stage, where COVID-19 waste is collected manually with two different colors, yellow color-coded bags for incinerated waste that cannot be disposed of into general waste or recycling waste streams, and red bags for infectious PPEs, similar to the United Arab Emirates regulation. After that, waste will be segregated by a system of color coding for waste containers, as mentioned in the collection stage. Then, the Storage and Transportation stage, where waste bags must be properly labeled and stored in a secured, ventilated, and cleaned storage room to be transported afterward from the facility to the truck by disinfected trolleys. Trucks pathway should be reported earlier, in addition to the collected waste type, quantity, driver's name, date, and time. It is important to separate the general waste from the medical waste at the storage and transportation stage. Thus, an isolated COVID-19 waste storage bin must be used to preserve COVID-19 waste in a special temporary storage room to avoid mixing it with other types of waste. Finally, the Treatment and Disposal stage, where a manual coordinator is required to approve the manual segregation of the waste for each treatment or disposal method, or sometimes merged methods for the same waste type (Andeobu et al. 2022).

However, most of the generated frameworks were determined for COVID-19 waste only neglecting future pandemics with different contagious viruses, other than the COVID-19 virus. Also, most of the frameworks focus on the disposal/treatment, recycling, or segregation methods, neglecting the overall strategy. Another point is that the facilities dedicated to COVID-19 proposals were closed after the pandemic; therefore, governments have to establish a plan to operate those facilities within our normal situations and during emergency circumstances. Therefore, by the end of this paper, we are going to produce a detailed sustainable emergency protocol to be followed in future pandemics and show the steps to be followed to reduce the infectious rate and give a spontaneous plan to defeat the pandemic side effects.

3. Methods

This study follows a systematic literature review (SLR) approach utilizing previous medical waste and COVID-19 infectious waste papers. The goal of this paper is to systematically find reliable studies and identify weaknesses and gaps in those studies. The papers reviewed are filtered depending on the researched language (English), year of publication 2019 to 2022, study type, and methodology. Papers are selected from international academic databases like Science Direct, Springer, Web of Science, Research Gate, and Google Scholar. The guidelines for COVID-19 Waste Managementand strategies proposed by World Health Organization (WHO), the United States Occupational Safety and Health Administration (OSHA), and the European Union, are also included.

4. Results and Discussion

The construction of a waste management framework necessitates an examination of schemes and locations at which waste is generated, as well as the many categories into which it may be segregated or otherwise classified. Following that, waste management is divided into many stages, beginning with waste collection and ending with waste treatment and disposal. Details on these aspects are covered next.

4.1 Generation of Biomedical Waste

Medical waste comprises materials generated in healthcare environments such as medical wards, laboratories, diagnostic clinics, medical equipment, and materials contaminated by body fluids, blood, or cultures, among others. During the pandemic, it was extremely challenging to deal with the sudden rise in the amount of clinical waste along with a decreased capacity of personnel managing the waste. The rising number of sick patients and people visiting the hospital for diagnosis meant an increasing utilization of personal protective equipment (including gloves, gowns, face shields, masks, etc.) by the healthcare workers and staff tending to them as well as contaminated and soiled wastes from patient care and use. Furthermore, the considerable amount of screening tests for the infected cases and other work, travel and leisure purposes, also generated unusually larger amounts of waste materials from the testing kits, swabs, packaging containers, and chemical wastes from the PCR cartridges. Moreover, ever since the introduction of the COVID-19 vaccines, governments across the world have been aiming to provide rapid immunization to their citizens and residents by setting up mass vaccination centers, which have been causing an increase in the number of discarded vaccination vials and needles among other things. Activities like these ultimately generate a significant quantity of pandemic-related waste that sometimes require special handling, as outlined in Table 1. Hence, in order to efficiently manage discarded and hazardous waste, it is important to have a systematic control and management program in place (Ilyas et al. 2020).

Table 1. Most common pandemic-related biomedical waste materials. Adopted from (W.H.O., 2022).

Material	Type			Special Handling
	Infectious	Non-hazardous	Other	
Masks	✓			✓
Gowns	✓			✓
Gloves	✓			✓
Vaccine Vial		✓		✗
Vaccine Needle			Sharps	✓
PCR testing cartridge			Chemical	✓ (has guanidium thiocyanate)
Plastic containers		✓		✗

Clinical waste can give rise to several biohazards at the various levels of its handling, starting from its source, and hence, proper identification and close monitoring at its point of generation are among the critical aspects of a successful waste management program. Depending on the site of waste generation, the volumes and the preferred treatment methods of different categories of waste could be varying. For instance, during the COVID-19 pandemic, large volumes of contaminated nasal swab tips were disposed of in a nucleic acid testing center compared to the considerable amount of sharp wastes, viz. used needles, produced at the vaccination centers. The waste generation points can be broadly classified into healthcare-related units or public/community spaces, as illustrated in Figure 3. Generally, the hospitals and other medical environments will involve more skilled/trained personnel as well as an already existing biohazard management system (Capoor and Parida 2021; Rajak et al. 2022; Saxena et al. 2022). The major challenge, however, will be the proper management of the suddenly rising influx of clinical waste while safeguarding the staff and patients from the risks associated with it. Moreover, during the pandemic, several temporary facilities like mass screening/diagnostic centers and vaccination units were also built to deal with the accelerated prevention of infection spread in the communities- all of which were generating an enormous quantity of clinical and other waste. On the other hand, the common people require additional awareness training along with the enforcement of new regulations in order to be better capable of dealing with the produced and contaminated wastes in their homes, offices, and other public spaces. Nevertheless, in both cases, a clearly laid out framework dealing with biomedical waste management will help the stakeholders of the various institutions in minimizing the hazards arising out of it (Agamuthu and Barasarathi, 2021; Mekonnen et al. 2021; Singh et al. 2020).

Among the various materials disposed of during the COVID-19 pandemic, face masks, in particular, constituted a very large proportion of the generated biomedical waste since their constant use was mandated to reduce the transmission from an infected person. Face masks were considered an essential part of the protective personal equipment offering the first level of defense against the virus since it could transmit easily respiratory droplets in the air (Kalantary et al. 2021; Ngoc et al. 2022; Sangkham 2020; Tsai 2021).

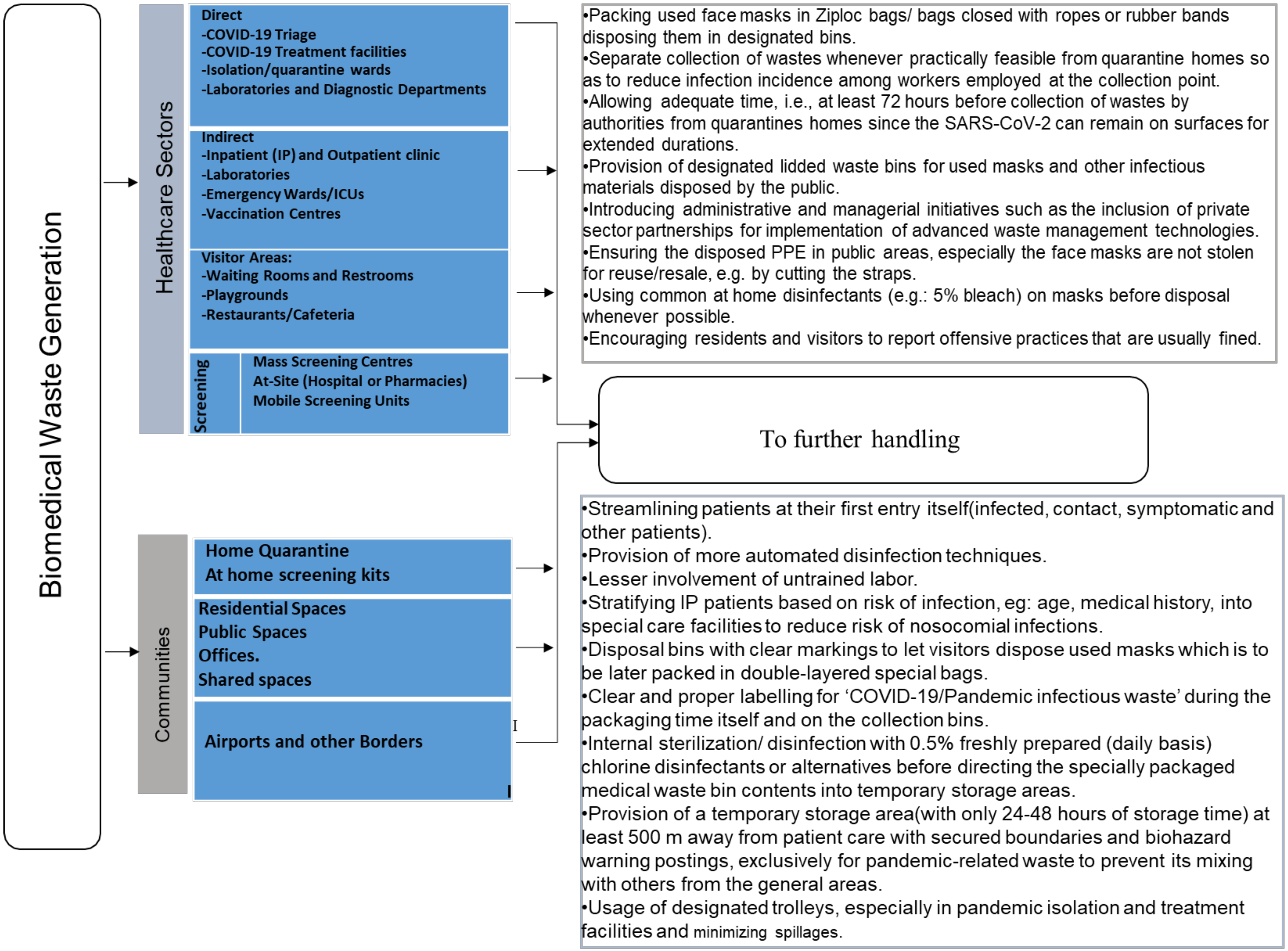

Figure 3. Major generation points for pandemic related clinical waste

Figure 4 shows the number of face masks used daily in different countries as adapted from the works of Sangkham et. al in 2020 (Sangkham 2020). The accumulation of the disposed facemasks in nature reserves, public spaces, and other areas not only posed a serious threat to the environment but also contributed to the risk of infection transmission since the virus articles could remain active on their surfaces for up to several hours (Ilyas et al. 2020). Therefore, it is important to properly regulate the disposal of single-use face masks. Some of the measures adopted for discarded face mask management by countries like, India, China, Bangladesh, Indonesia, Malaysia, Thailand, and Nepal were summarized by Sarawut in 2020 (Sarawut 2020). Lessons learned from them will prove to be pivotal in the management of a high number of disposed of wastes in the event of a similar infection spread or pandemic.

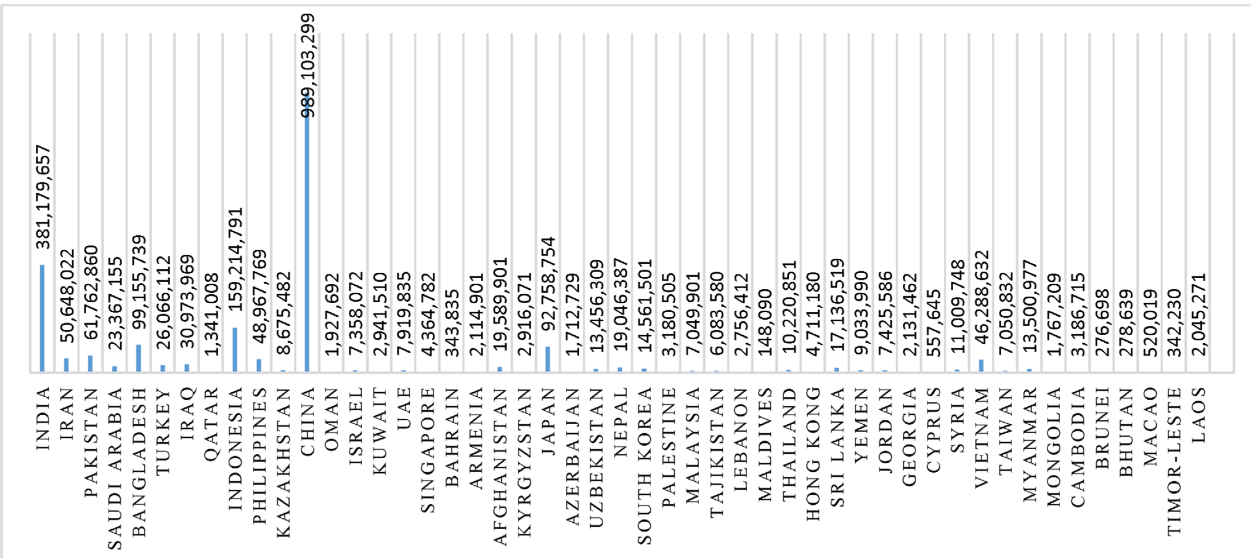

Figure 4. Estimated total number of daily face masks by different countries. Adopted from (Sangkham 2020).

Figure 3 also shows some commonly advocated measures to deal with the generated medical waste so it may be treated safer and more efficiently. It is important to realize that every institution must be responsible for defining a clear set of regulations best fitting the organizational priorities and capabilities while collaborating with the local or national authorities. Most countries have regulations and protocols dealing with biomedical waste and its management already in place. Most commonly, government authorities will have specialized departments regulating and enforcing the guidelines on the treatment and disposal of clinical waste. However, in the event of a pandemic like COVID-19, the capacities and logistics of these sectors are severely under pressure, especially those in developing or underdeveloped regions. The existing treatment facilities may not be equipped to accommodate the large volumes of waste being generated due to the pandemic control protocols and could be significantly restrained due to this high rate of waste generation. Hence, the already practiced frameworks will require a modification or introduction of specific aspects of clinical waste management.

Table 2 illustrates some common approaches introduced by several well-known organizations around the globe which have been adapted from the work of (Ganguly and Chakraborty 2021). Despite the fact that there is no unanimous agreement on the total isolation of COVID-19-related waste from other clinical waste, experts and regulating bodies constantly advocate for practices that minimize the risk of infection spread and biohazards that could emerge during the waste handling procedures. These measures should be feasible using the available resources and infrastructure in that region. Hence, pandemic-related waste management approaches adopted must be tailor-made to fit the local limitations, constraints, and capabilities.

In the UAE, several adoptive practices are prescribed and regulated in accordance with the principles and suggestions developed by organizations like the World Health Organization (WHO), Center for Disease Control & Prevention (CDC), National Crisis and Disasters Management Authority (NCEMA), Ministry of Health and Prevention (MOHAP), Abu Dhabi Public Health Center – (ADPHC), Department of Health (DOH) and the Dubai Health

Authority (DHA). The Ministry of Climate Change and Environment, U.A.E. have also released a comprehensive guide on the standards and practices for the effective and safe disposal of clinical waste produced during the several phases of COVID-19 patient handling in its third edition of the Infectious Biological Waste Management Handbook. Figure 5 provides a summary of the most important guidelines it encompassed (M.O.C.C.A.E 2021).

Table 2. Measures proposed by several organizations for COVID-19 waste management. Adopted from: (Ganguly and Chakraborty 2021)

OSHA (Occupational Safety and Health Administration, US)	Sanitization workers must use appropriate personal protection equipment (PPE) Pandemic-related wastes from wards are to be treated like other medical waste since COVID-19 is not a category A infection.
WHO (World Health Organisation)	Proper segregation of clinical waste in a designated colored bin. Infectious wastes produced from patient treatment are to be disposed of onsite by autoclaving, high-temperature treatment, or incineration. Alternatively, controlled burning waste is preferred when the above treatments are unavailable.
CPCB (Central Pollution Control Board, INDIA)	Color-coded collection bags/bins for classification of wastes. Pandemic waste is collected and temporarily stored in a room before handing it over to concerned trained authorities. General or non-hazardous waste is to be treated following already existing guidelines.
EU (European Union)	Recommended provision of individual waste bags to patients for disposal of infected materials followed by sealing.
SNPA (National System for Environmental Protection)	Municipal solid wastes(MSW) from residential units infected patients must be collected in double-layered bags, and sterilized afterward. MSW from non-infected/quarantine houses could be collected in double-layered bags by PPE-equipped sanitary workers.

Proper segregation and classification of the generated waste are one of the most critical aspects in the safe and systematic control of medical waste. When the wastes are classified into their appropriate category at the site itself, it will allow the system to function more effectively while easily enabling the disinfection or disposal treatments most appropriate for each category of waste. Segregation of waste helps in the reduction of contamination by hazardous wastes and easier transportation and storage. The classification of medical wastes' can be based on several parameters, for example, by the type, composition, or disposal method. Most countries have regulations that mandate the classification categories to be followed, and if not, the authorities in power should evaluate and identify the most suitable divisions based on their existing collection capabilities, waste treatment capacities, and routes. A very common and accepted approach for waste segregation is a system of color coding for waste containers. The use of colors for different categories of waste and its allotted leak-proof and closed bins make it possible for employees and other users to identify the appropriate bins easily while providing a visual indication of the possible hazards from each category.

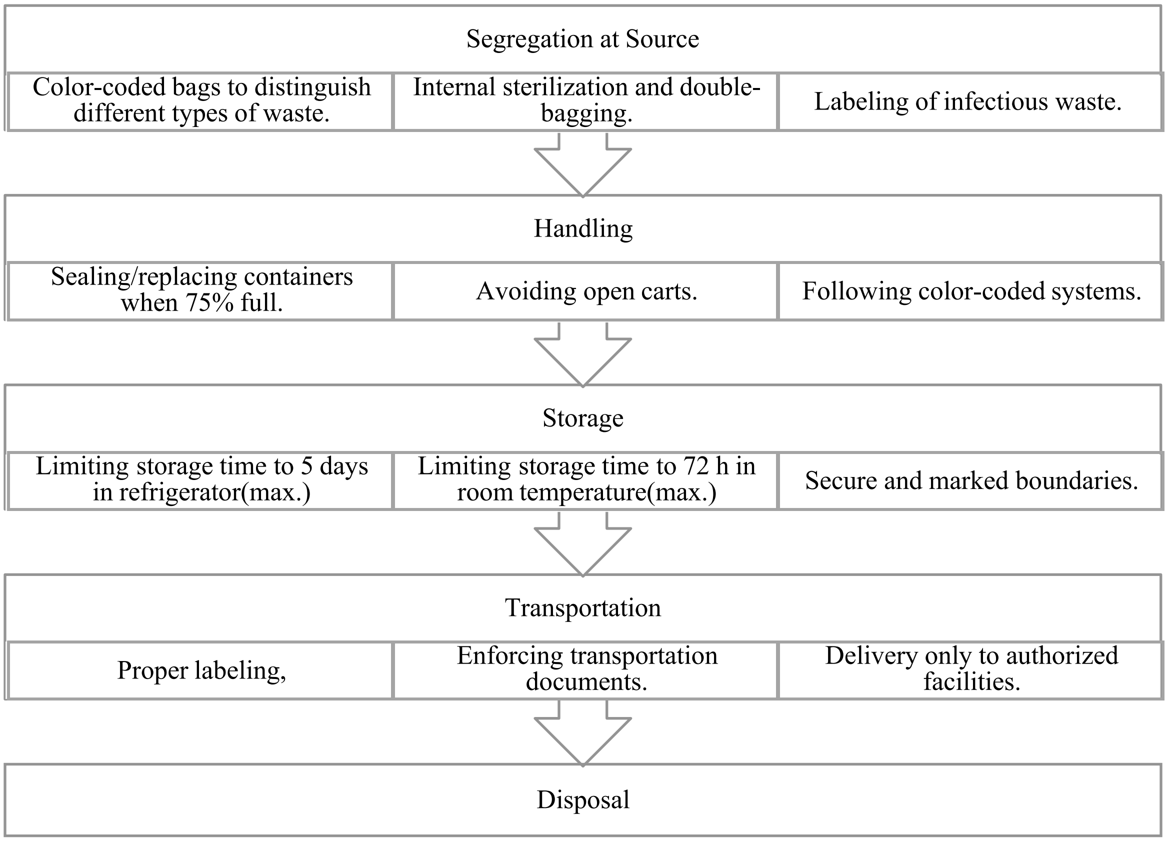

Figure 5. Summary of the important guidelines in the U.A.E. for COVID-19 clinical waste (M.O.C.C.A.E. 2021).

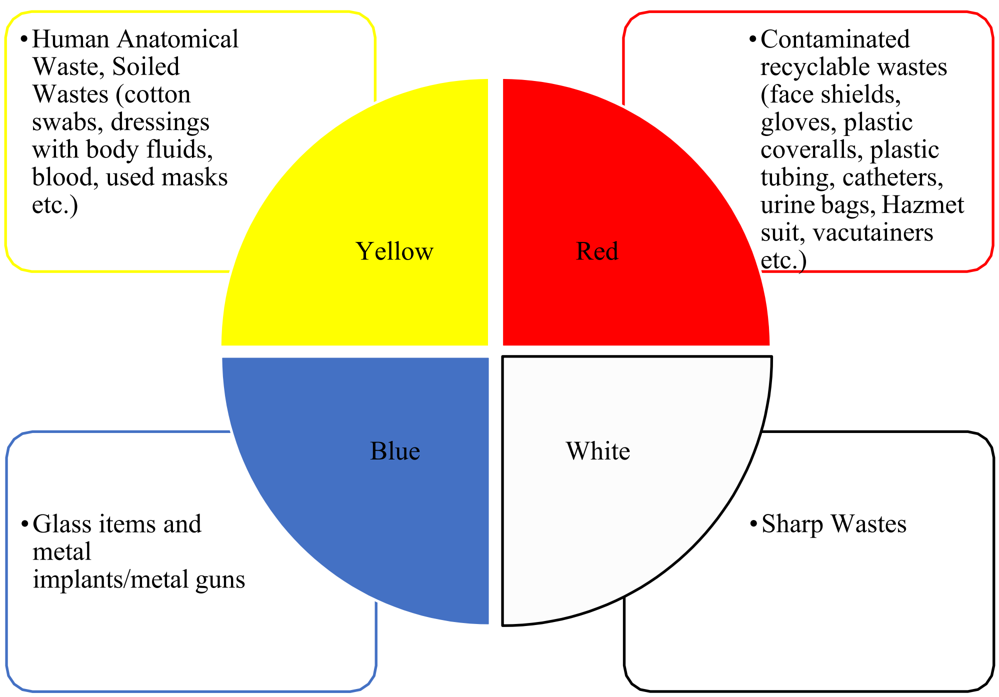

Figure 6. An illustration of a color-coded classification for medical waste (C.P.C.B 2020)

4.2 Waste Management Phases

Since the emergence of the pandemic, several authorities have established different systems to manage the waste produced by the pandemic. Due to the highly transmittable nature of the COVID-19 virus, many of these waste systems have established precautionary measures to protect the workers handling the waste. One method employed by (Singhet al. 2022) is through disinfecting the waste at the source prior to the arrival at the facility, where internal disinfection takes place before knotting the sealed bags and inside the storage rooms prior to the collection. Many of the current existing waste management systems adopted by different countries have tried to address the need to establish waste management systems that are effective in terms of handling waste yet safe enough for the public and the environment.In order to address the needs outlined above, the UAE government has taken steps to meet them. Therefore, one of this paper's objectives is to outline and review the waste management practice adopted across several emirates in theUAE. A more comprehensive and systemic approach has been developed based on our findings in the literature. The waste management system that has been established in the UAE can be summarized in four different phases as follows:waste collection from the source, transportation to dedicated facilities, sterilization upon arrival, and waste treatment.

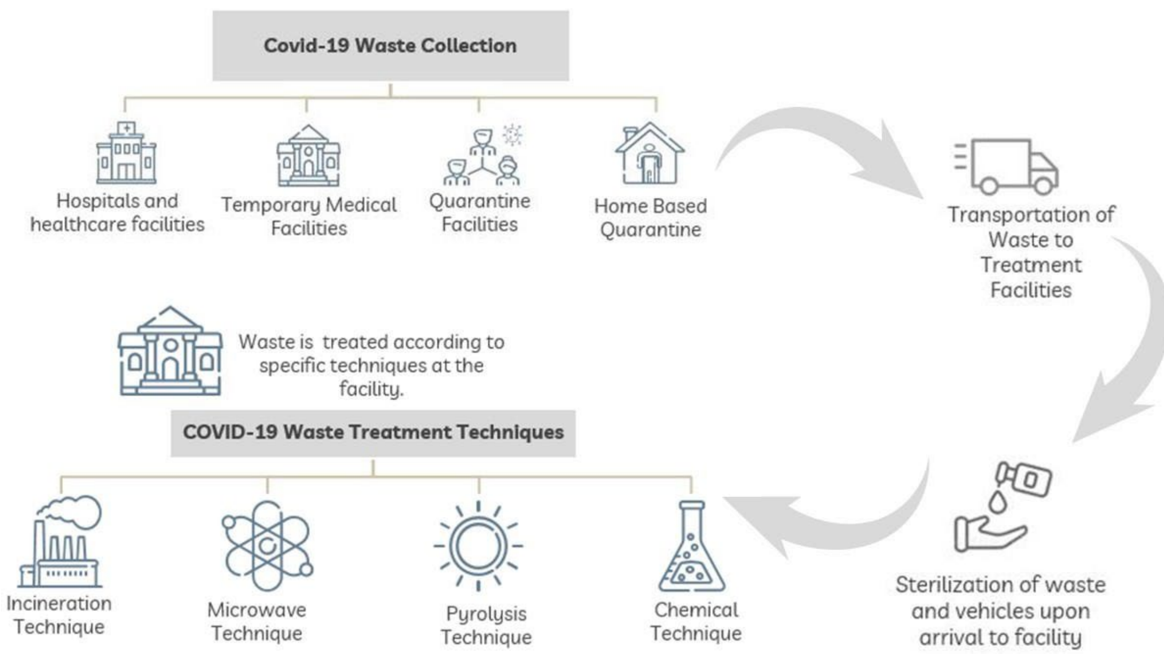

Figure 7. Framework proposed for the waste

management**Phase 1: Collection of COVID waste from source**

The first phase of the waste management plan starts by collecting COVID waste from healthcare facilities, quarantine facilities, home-based quarantine waste, and field hospitals. As a faster response to the outbreak of the pandemic alongside easing the pressure on the medical staff, the UAE government has launched several field hospitals across different emirates to withstand the load of the infected population. According to Al Hosany et al. (2021), the first field hospitalwas launched at the emirate of Dubai at the world trade center to incubate patients who tested positive to minimize the spread of the disease. Additionally, several other field hospitals were established across the emirate of Abu Dhabiby the Abu Dhabi Health Services Co (SEHA) (Al Hosany et al. 2021). Apart from that, SEHA has also established a quarantine facility that can accommodate up to 1000 patients (Chiranjib Sengupta 2020).

Phase 2: Transportation of medical waste

The medical waste generated by all the healthcare facilities across the emirate of Dubai is handled by Dubai Municipality, where they are collected and transported to Jebel Ali Hazardous Waste Treatment Facility as reported by Dubai Municipality. As revealed by the general director of Dubai municipality, approximately 350 tons of waste was treated by the Jebel Ali facility from the start of the pandemic till the end of April 2022 (Dubai Municipality 2022). The vehicles used to transport waste to the facilities are designed to be closed, secured and temperature controlled. These vehicles are also embedded with a waste tracking system that registers the time waste was received from the source, and the time of arrival at the facility alongside the route taken (Awad et al. 2021). In the emirate of Abu Dhabi, the waste is managed by Abu Dhabi's waste management company Tadweer (Euronews 2020). To support the measures taken by the government to control the spread of the virus, Tadweer has launched three mobile medical waste incinerators to be operated at three different locations which are: Al Mafraq Hospital, the fieldhospital at Abu Dhabi National Exhibition Centre (ADNEC) and the Emirates Field Hospital in Mohammed Bin Zayed City (Illankoon 2020).

During the transportation phase, the Internet of Things (IoT) technology will be used to link the overall transportation process. At the facility, there will be smart sensor-based waste bins to detect and evaluate the type of waste based on the proposed classification. Those bins will be connected to a cloud database to notify an automated waste collection system, once bins are filled. An automated automobile truck will collect the waste from each facility, storing each type of waste in specific containers. The details of the waste type and weight, collection time, used pathway, truck details, and delivery time must be reported and shared via the cloud database with the operator in the factory. Afterward, the waste collected will undergo the classification phase (Andeobu et al. 2022).

Phase 3: Segregation of waste

The segregation phase is essential to determine the proper treatment or recycling technique for each classified group; otherwise, it will initiate domestic solid waste infection with the virus. 85 percent of the waste collected from healthcare facilities is actually non-hazardous waste (Hantoko et al. 2021; Andeobu et al. 2022). Thus, an automated method will be used to classify each category in the segregation phase, based on machine learning and Artificial intelligence techniques. This will benefit governments economically and environmentally. The waste groups will be distributed into four color-coded groups, as mentioned in the classification part earlier, using a waste image dataset and artificial intelligence. The waste segregation will be performed by a robotic arm and a decision-level fusion system for an effective waste management system. In the fusion level, 100 pre-processed images database will be implemented using MATLAB (MathWorks Inc, USA), with a feature texture of histogram frequency-based domain. Then, waste will be classified using a Support Vector Machine (SVM) classifier, a machine learning model with MATLAB algorithms, for the waste type recognition automation step (Andeobu et al. 2022).

Phase 4: Sterilization of COVID-19 virus

The sterilization phase has been introduced with the emergence of the COVID-19 pandemic, where medical waste contaminated with the virus is sterilized upon arrival at the treatment facility. The urge to act fast and dispose of the contaminated waste to eliminate the contingency for the workers at the facility was on top priority for the coordinators for the disposal process to take place as soon as it arrives at the facility. It is worth noting that depending on the protocol followed by each emirate. The sterilization takes place at every step prior to the arrival at the facility as an extra precautionary measure. In the emirate of Dubai, the frequency of sterilization starts from the disposal and sealed bags and is repeated once it reaches the temporary storage room before departing to the treatment facility and finally upon arrival at the treatment facility (Dubai Municipality 2022).

Phase 5: COVID-19 waste treatment

Several waste management techniques have been adopted by different countries to handle COVID-19 waste. Some of these techniques include incineration, steaming, thermal, and microwave. The selection process of the appropriate disposal techniques depends on several factors, such as quantity, cost, and waste type (Hughes 2020). During the pandemic, techniques that use thermal energy and heat have been relied on heavily as safe disposals of contaminated waste with the Sars virus to avoid the spread of the disease. As was reported by several works in literature, the discarded material and waste produced by COVID is considered hazardous waste as it poses a potential threat to the workers to whom they are exposed to the virus. The waste treatment methods can be further divided into two categories: Off-site treatment and onsite treatment methodology.

4.3 Offsite and Onsite Treatment

The off-site waste treatment takes place outside the source producers but rather takes place in specific waste treatment facilities. The incineration treatment approach is considered one of the commonly used techniques to handle COVID-19 viruses, as the utilization of heat ensures the pathogens are killed. These facilities are equipped to handle medical waste of up to 300 kg per hour where the temperature is up to 1200 degrees (Dubai Municipality 2022).

As one of the initiatives taken by the UAE government to meet the high demand for treating waste contaminated by COVID-19, the government has responded by supplying mobile medical waste incinerator units at various locations across the UAE (Illankoon 2020). These units have proven to treat contagious waste on sites reducing the storage of the waste and easing the handling load of waste upon the off-site treatment facilities. Some other techniques include pyrolysis, microwave, and chemical disinfection. Figure 7 provides insight into the adopted framework that handles COVID-19 waste (Keishamaza Rukikaire 2020).

4.4 Generalized Waste Management Framework for Future Pandemics

One of this paper's objectives is to adopt a generalized framework based on the COVID-19 framework to be used as a reference for handling waste produced by future pandemics and outbreaks that are caused by biological agents such as viruses and bacteria. It can be thus suggested to handle the waste based on the following chronological sequence of steps starting from collection of the waste from different source producers such as hospitals. Secondly, the transportation of the waste with the highest precaution taking into consideration the transmission mode of the biological agent, then moving on to the sterilization phase upon arrival. Although many research works suggest that sterilization upon arrival is enough, some researchers believed that the disinfection phase must be enforced at every step, starting from disposing and ending up with the treatment. Lastly, depending on the nature of the biological agent and transmutability features, a proper treatment technique can be chosen to handle the waste produced by it. Figure 8 below shows a summary of the proposed generalized framework that handles waste generated by a biological agent.

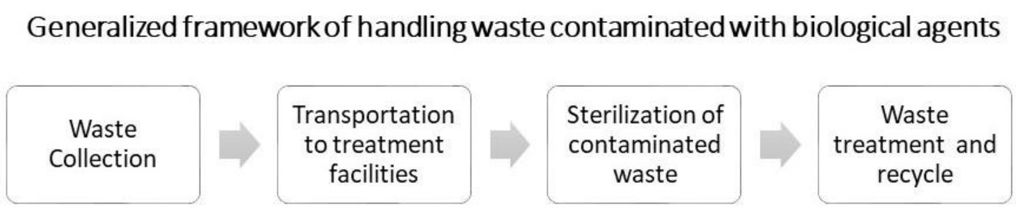

Figure 8. Generalized waste management for future pandemics

4.5 Managerial Waste Management

A relatively recent term in the field of waste management is "Integrated Waste Management," which improves several established waste management procedures while incorporating new dimensions of waste management systems (Seadon 2006). Technological development, waste treatment, and others are examples of the technical elements of integrated waste management, whereas policy practices and awareness programs are examples of the non-technical aspects of waste management. Figure 9 illustrates the non-technical aspects of a holistic waste management system that pertain to the managerial aspect of waste management.

Figure 9. Aspects of the managerial waste management

The first aspect of managerial waste management is the establishment of national guidelines, which act as a critical element in helping firms provide efficient waste management. Setting up the guidelines should be done by communication, which allows for the development of shared understanding and the elucidation of complex situations. Next, facilities are better able to achieve the goals established by the administration with the help of the policies implemented. The rules established for the treatment and deployment of biological waste management are included, as are periodic revisions of the guidelines to account for changing circumstances on the national and international levels (Deepak et al. 2021). The next step is for authorities to permit healthcare facilities to produce, collect, and transport biological waste to processing facilities. This paves the way for a structured hierarchy to be set up, with clear lines of accountability between various institutions and entities. Finally, a crucial step in the managerial perspective of waste management is public awareness. The success of waste management services depends on open lines of communication between municipal agencies and their consumers. In order for citizens to make effective use of the services that are made accessible to them, it is necessary that they are aware of the services' schedules as well as any requirements for access and utilization. Campaigns, informative multimedia presentations, and professional assistance and guidance in public areas are all examples of awareness-raising initiatives.

5. Conclusion

Increased usage of personal protective equipment (PPE), disinfectant wipes, and other healthcare supplies has been linked to the pandemic, leading to a rise in the production of a variety of potentially infectious wastes. Therefore, the establishment of a strategy for handling solid waste is becoming more pertinent. The comprehensive framework developed in this work emphasized the efficient implementation of various waste processing technologies that were implemented in response to the COVID issue. It also illustrated the effective management of various types of medical solid waste. One pitfall is that the SVM model is more expensive than other technologies as it needs advanced computational resources. In spite of the current COVID-19 pandemic, this study addresses waste management strategies that can be used to cut down on waste production. Light is also shed on prospective waste management scenarios for future pandemics.

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