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Disinfection technology and strategies for COVID-19 hospital and bio-medical waste management

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HIGHLIGHTS

• New category of bio-medical waste has emerged after COVID-19 outbreak.
• Disinfection of COVID-waste is necessary to control the mass spread of pandemic.
• Effective management of COVID-waste is challenging to mitigate the health risks.
• Policy briefs essence a combined approach by environmental and medical researchers.

GRAPHICAL ABSTRACT

Abstract

The isolation wards, institutional quarantine centers, and home quarantine are generating a huge amount of bio-medical waste (BMW) worldwide since the outbreak of novel coronavirus disease-2019 (COVID-19). The personal protective equipment, testing kits, surgical facemasks, and nitrile gloves are the major contributors to waste volume. Discharge of a new category of BMW (COVID-waste) is of great global concern to public health and environmental sustainability if handled inappropriately. It may cause exponential spreading of this fatal disease as waste acts as a vector for SARS-CoV-2, which survives up to 7 days on COVID-waste (like facemasks). Proper disposal of COVID-waste is therefore immediately requires to lower the threat of pandemic spread and for sustainable management of the environmental hazards. Henceforth, in the present article, disinfection technologies for handling COVID-waste from its separate collection to various physical and chemical treatment steps have been reviewed. Furthermore, policy briefs on the global initiatives for COVID-waste management including the applications of different disinfection techniques have also been discussed with some potential examples effectively applied to reduce both health and environmental risks. This article can be of great significance to the strategy development for preventing/controlling the pandemic of similar episodes in the future.

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1. Introduction

Bio-medical waste (BMW) has remained the source of emerging pollutants categorically generated by healthcare practices like medical diagnosis, treatment and immunization of disease, and/or biological research activities on animals (Datta et al., 2018). It also includes the medicine excretion by patients wherein the active component of drugs and metabolite, chemical and pharmaceutical residues, iodinated contrast media, etc. (Chartier et al., 2014). Approximately 85% of total BMW volume is regarded as non-hazardous waste (WHO Health-care waste, 2018), while the remaining volume comes under infectious hazardous wastes. The improper disposal of hazardous bio-medical waste (HBMW) poses severe risks to public health and the environment as it acts as a host of variety of pathogenic microorganisms. Pathogens present in HBMW if not managed well may enter the human body through a puncture, abrasion or cut in the skin, mucous membrane, inhalation, and ingestion. Respiratory infections, gastroenteric infections, skin infections, haemorrhagic fevers, baceteriaemia, viral hepatitis, influenza are some of the common diseases caused by exposure to HBMW (WHO, 2014). Studies conducted in Brazil, Greece, India, Iran, and Pakistan has revealed that a significant prevalence of virus infection in (bio-medical/solid) waste collectors can be traced directly to pathogens in contaminated waste (Singh et al., 2020; WHO Health-care waste, 2018). Therefore, effective management of HBMW is highly imperative to control the stemming transmission of infections. In this context, the World Health Organization (WHO) has directed the core principles in June 2017 by stressing on the right resource investment and complete commitment to reduce the health adversities and environmental pollution (Datta et al., 2018).

In the recent decade, coronaviruses have caused large-scale pandemics namely, severe acute respiratory syndrome coronavirus-1 (SARS-CoV-1) and the Middle East respiratory syndrome (MERS). Anew outbreak in this family is added in November–December 2019 as the novel coronavirus disease-2019 (COVID-19) caused by a large group of highly diverse, enveloped, positive-sense, and single-stranded RNA viruses namely, SARS-CoV-2 (He et al., 2020). Soon after pneumonia disease outbreak in Wuhan (in Hubei province of China), the transmission of COVID-19 has been found by human-to-human contact and declared a pandemic of global crisis. Although the genomics sequencing and entry pattern of SARS-CoV-2 into human cells are the same as SARS-CoV-1, the mushroom-shaped spikes (s-)proteins help to maintain the van der Waals forces to intact with the human cellular receptor-ACE2 (as the schematic is shown in Fig. 1). The binding affinity of SARS-CoV-2 is 10- to 20- folds higher than SARS-CoV-1 (Chan et al., 2020). The high affinity of S-proteins for human ACE2 may facilitate the rapid transmission of SARS-CoV-2 in human population (Wan et al., 2020; Xu et al., 2020). Consequently, COVID-19 has wreaked havoc and became a matter of severe global concern. Until now, no specific drug or vaccine is specifically known to treat COVID-19 patients. Mass sampling with rapid tests, isolation of suspects/patients, use of personal protective measures, social distancing, and life-supporting treatments are known countermeasures to prevent/fight this fatal pandemic. Personal protective equipment (PPE), surgical (and protective) facemasks, aprons/gowns, and nitrile gloves are essentially used to protect individuals from exposure to pathogens and contaminants (Singh et al., 2020). Traditionally, these protective measures have been predominantly used against pathogens in hospitals. However, COVID-19 has necessitated their usage in domestic isolation and individual protections, leading to a rapid accumulation of potentially infectious waste streams (hereinafter, COVID-waste). The entire world is, therefore, facing an unprecedented challenge to fight COVID-19 together with the myriad COVID-waste.

The drastic increase in COVID-waste from 40 tons/day to 240 tons/day in Wuhan and estimated increase from 5 million tons/year to 2.5 million tons/month in the US is scary if not treated properly. Since the pandemic outbreak, South Korea has generated about 2000 tons of COVID-waste until the starting of May 2020 (ESCAP, 2020). Moreover, an increase in PPE supplies by 40% per month from the current compounded annual growth rate (CAGR) of 6.5% is projected (Market Reports, 2019). The demand for PPE including the facemasks and surgical gloves are not expected to decline during the post-pandemic period and estimated a 20% CAGR up to 2025 (WHO, 2020). The drastic increasing number of regions/countries/people infected with SARS-CoV-2 has indicated that the world will overrun by COVID-waste and the outcome of this glut will have a deep impact on sustainable waste management practices in the coming years (Cutler, 2020). The resilience of our society and waste management practices are under tests with the stability reports of SARS-CoV-2 (Kampf et al., 2020). The traces of this virus has been observed on plastics for 6.8 h, stainless steel for 5.6 h (van Doremalen et al., 2020), and the outer layer of surgical mask up to 7 days albeit a lower cell density of about 0.1% of the original inoculum (Chin et al., 2020). It clearly indicates that COVID-waste (like needles and syringes used for blood samples, surgical facemasks, and PPE) can have a longer persistence of SARS-CoV-2. Virus transmissions from the contaminated dry surfaces have been postulated including self-inoculation of mucous membranes of the eyes, nose, and mouth (Otter et al., 2016). The exposure to COVID-waste may potentially increase the virus spread by increasing the reproductive number (R0) from its determined range between 2.2 and 3.58 (Li et al., 2020; Zhao et al., 2020). The viral loads of saliva, cough, tears, and urine remained with COVID-waste can potentially be a host-carrier of SARS-CoV-2. The major route of SARS-CoV-2 transmission is splatters liberated during breathing and/or, expelled through sneezing of an infected person. The improper discharge of COVID-waste without disinfection treatment would expose common people and healthcare workers in danger of infection spread.

Thus, effective management of COVID-waste including the appropriate disinfect and disposal techniques are necessary to control the pandemic spread, which has not been focused yet albeit posing a similar threat as SARS-CoV-2 itself can have to the public health. The present article reviews the disinfection technologies to control/prevent the novel coronavirus spread and the proper management of COVID-waste including the effective strategies and reprocessing possibilities of the used items.

2. Review methodology

To outline this review paper on the topic presented herein, the first step was to extract articles using the initial keyword “disinfection technology, strategies, and management of COVID-19 hospital waste and bio-medical waste”. With the initial keyword searched in the Scopus database, a total 61,442 results appeared (that included 2705 journals; 46,875 books; and 11,862 webpages) albeit mostly belong to the common BMW and not the COVID-waste. A further change in keywords like “COVID-waste management” (611 journals and 5024 webpages); “disinfection of COVID-waste” (2652 journals and 11,311 webpages); and “Management strategies for COVID-waste” (2361 journals and 10,967 webpages) were also searched. Notably, no books were found to exist until the search date (May 6, 2020) on COVID-19 waste; whereas, the reports and data published in webpages were found informative to shape this review article. Therefore, the search engine like Google was also used to fetch the recent information and developments on the handling of COVID-waste worldwide with different keywords as stated above. To ensure relevance to the topic of this review article, 142 items were manually screened out by keywords, title, abstract, and when unsure, by assessing the full text. Finally, excluding studies did not focus on COVID-19 waste, 51 items were found relevant and referred along with personal communication with BGL Private Ltd. The materials like ACR Plus (2020), Barcelo (2020), Datta et al. (2018), ESCAP (2020), Shereen et al. (2020), Wang et al. (2020) and time-to-time guidelines given by WHO and CPCB (2020a, 2020b, 2020c) were particularly helpful in this context. The personal information gathered
from the Bio Genetic Laboratories (BGL) Private Ltd. (India) and Ministry of Environment (South Korea) were much useful to understand the entire scenario and real-time system on disinfection techniques for COVID-waste and their management practices.

3. Strategies for disinfection of COVID-waste

Classification of hospital waste is the first step for the management of COVID-waste (refer Fig. 2). It is the best practice that the waste is classified at its origin. This strategy is not only time-efficient but also avoids the chances of infection spread to other handlers of the waste. The collection of COVID-waste in separate bags/bins is directed to have a clear marking over the dedicated bins. At the time of waste classification, the waste containing bags must be disinfected and sealed in double-layered plastic bags (usually yellow color) prior to transportation from the originated place/ward. Commonly, the BMW contains about 85% of general non-infectious waste, 10% of infectious hazardous waste, and 5% of radioactive and/or, chemical waste (Datta et al., 2018; WHO, 2014; WHO Health-care waste, 2018).

All COVID-waste comes under the hazardous BMW. Once identified, the segregation becomes an easy task for their separate storage from where the waste can be collected on a priority basis and within the deadlines. While doing so, proper disinfection of the storage area and the transporting vehicles carrying COVID-waste to common biomedical waste treatment and disposal facility (CBMWTF) becomes necessary. For the disinfection of COVID-waste, various factors like the quantity and type of waste, costs, and maintenance are considered for selecting the appropriate disinfection technology (as shown in Fig. 3).

It suggests that incineration at higher/lower temperature can be adopted on the basis of waste volume to be treated and the investment capacity. Else if, the operational scale of a hospital is smaller with limited investment that cannot afford the installation and maintenance costs of incinerator, the chemical disinfectant (as front disinfection technique) in combination with microwave and steam disinfection technique at the latter stage and relatively a lower temperatures (between 93 and 540 °C) over incineration (usually at 800–1200 °C) can be preferred. A comprehensive discussion on each disinfection and disposal technology has been presented below.

4. Disinfection and reprocessing techniques

4.1. Disinfection using incineration

Incineration is based on high-temperature combustion range between 800 °C to 1200 °C that completely kills the pathogen and potentially burns up to 90% organic matters (Datta et al., 2018; Wang et al., 2020). As per the BGL Private Ltd. (a common bio-medical waste treatment facility approved by the Jharkhand Pollution Control Board, India), the most of the COVID-waste are sent to incinerate at a temperature > 1100 °C. Sometimes, the residual mass is re-incinerated with fresh charge depending upon the volume reduction of COVID-waste. As shared by BGL, a number of toxins are produced in-situ like furan and dioxins have a high tendency to accumulate in fatty tissues and cause damage to the immune and endocrine system. Therefore, the flue-gas treatment facility is also required with the incineration facility that costs additional burden to the operator. Consequently, running the facility with small quantity is somehow not viable and alternative technologies are applied.

4.2. Disinfection using alternative thermal techniques

There are mainly two types of alternative thermal technique available and in-practice to deal with COVID-waste, which are: (i) high-temperature pyrolysis technique, and (ii) medium-temperature microwave technique.

4.2.1. High-temperature pyrolysis technique

Pyrolysis is technologically sound technique than incineration. It usually operates in the temperature range of 540–830 °C that includes pyrolysis-oxidation, plasma pyrolysis, induction-based pyrolysis, and laser-based pyrolysis (Datta et al., 2018). In a pyrolysis-oxidation, the air measured below the theoretical chemical reaction is supplied to a fixed level of the primary combustion chamber. Wherein, the organic solid and liquid waste is vaporized at a temperature of ~600 °C under the air turbulence that leaves the residual ash, glass, and metallic fragments. In the second step of combustion, the flammable gaseous vapor is combusted in a chamber at a higher temperature ranges
between 982 °C to 1093 °C to the complete destruction of toxic substances like dioxins, releasing the clean exhaust steam. Looking at the rapid spread potential of SARS-CoV-2, using plasma-energy for a quick decomposition of COVID-waste is recommended than usual laser/gaseous combustion (Wang et al., 2020). Low emission rate, inert residual, volume reduction up to 95%, and mass reduction up to 90% have been observed with this technique.

4.2.2. Medium temperature microwave technique

This technique operates under the temperature range from 177 °C to 340 °C and includes reverse polymerization by applying the high-energy microwaves under an inert atmosphere for breaking down the organic matters. The absorption of electromagnetic waves (with a wavelength of 1 mm to 1 m in the frequency of hundreds of megahertz to 3000 MHz) increases the internal energy as the resultant vibration and rubbing of molecules. However, an inert environment created by nitrogen prohibits the combustion with oxygen to exhibit the high-temperature disinfection. Relatively lower energy and action temperature, limited heat loss, and less environmental burden with no toxic residue after the disinfection process are the main advantages of microwave technique. The specially designed microwave devices under strictly controlled process can prominently inactivate SARS-CoV-2. According to the report of Chinese Ministry of Ecology and Environment, this disinfection technique can achieve the logarithmic values of killing the hydrophilic viruses (Wang et al., 2020) and identified to be much helpful for an on-site disinfection of COVID-waste. The on-site disinfection avoids the risks posed by COVID-waste transportation that also saves time (Resilient Environmental Solutions, 2020). In the case of disinfection to COVID-waste, the microwave technique is also used in combination with autoclaving where steam is used for sterilization (in temperature range from 93 to 177 °C).

![Fig. 2. Schematic of the BMW/hospital waste generation to disinfection and disposal practices.](image)

![Fig. 3. Selection of disinfection technologies for BMW/hospital waste in different scenarios (adapted with permission from Wang et al., 2020. Copyright 2020, Elsevier BV).](image)
4.3. Chemical disinfection technique

The chemical disinfection technique is widely applied to pre-treat COVID-waste in combination with a prior mechanical shredding. The exhausted air is passed through high efficiency particulate absolute filter to safeguard against aerosol formation during the shredding. The crushed waste volume are further mixed with chemical disinfectants and kept in a closed system and/or, under the negative pressure for a given time. In this process, the organic substances are decomposed and the infectious microorganisms are inactivated or killed. The application of low effective concentration, stable performance, rapid action, and broad sterilization spectrum along with no residual hazards are the major advantages to use the chemical disinfectants as they not only effectively kill the microorganisms but also inactivate the bacterial spores (Wang et al., 2020). The chemical treatment of COVID-waste can be sub-divided into chlorine- and nonchlorine-based systems. In a chlorine-based treatment system, NaOCl or Cl₂ is used as the disinfectant media, where the electronegativity of chlorine helps in oxidizing peptide links and denaturing proteins that follows penetration of cell layer even at neutral pH. In fact, NaOCl is one of the first chemical disinfectants which releases the halo acetic acid, dioxins, and chlorinated aromatic compounds. Later, the use of ClO₂ increased which is a strong biocide, however, due to its unstable nature, it is used on-site. Moreover, it decomposes to form salt and less-toxic products which are non-reactive to alcohol/ammonia. On the other hand, H₂O₂ is commonly used as the disinfectant media in a nonchlorine-based treatment system. It acts to oxidize and denature proteins and lipids, consequently causing disorganization of the membrane via swelling of the saturated H⁺-ions. High reactivity and no toxicity associated with the chlorinated system is advantageous to use this system. Chemical solutions like povidone-iodine (˃0.23%), formaldehyde (˃0.7%), isopropanol (˃70%), and ethyl alcohol (˃75%) can also inactivate SARS-CoV-2 (Duarte and Santana, 2020).

4.4. Disinfection technique for reprocessing of personal protective

Notably, the potential use of disinfection technology cannot be limited to only a safety measure but its importance is much greater due to the global shortcomings in supply chain of personal protective after the outbreak of COVID-19 (Barcelo, 2020). Consequently, impromptu techniques for recycling of used personal protective are underway in some countries, albeit the high health-risk is associated due to improper decontamination (Mallapur, 2020; Singh et al., 2020). Hence, the effective disinfection technique is also required in terms of reprocessing of personal protective. Due to heat-sensitive properties, the aforementioned high-temperature disinfection techniques are not suitable that leads to reprocessing; whereas, the most prominent chemical disinfectant spray is found to degrade the inherent properties of personal protective (Rowan and Laffey, 2020). Instead of using the aqueous disinfectant solution, the use of vaporized hydrogen peroxide (vH₂O₂) has shown some encouraging results at sterilizing bacteria, prions, and viruses (Barcelo, 2020). A key proposition of low-temperature vH₂O₂ is polymeric material compatibility, while the reduced processing time (from 10 to 15 h using ethylene oxide to less than 6 h in a typical vH₂O₂ process) is an additional benefit that can be performed at atmospheric and in vacuum condition. However, compatibility with cellulose-based materials and ability to penetrate targeted surfaces are the limitations that have inhibited the application of vH₂O₂ in large scale due to the reduction of H₂O₂ strength in the presence of cellulose (McEvoy and Rowan, 2019). In a recent effort to disinfect N95 masks, Price et al. (2020) have investigated (i) dry heat (using hot air at 75 °C for 30 min) and (ii) ultraviolet germicidal irradiation (UVGI, at 254 nm and 8 W for 30 min). The study revealed that hot air treated N95 masks applied over 5 cycles do not degrade the fit of masks (change in fit factor, 1.5%; p-value, 0.67), while UVGI treated N95 masks applied over 10 cycles significantly degrade in fit and do not pass quantitative fit testing using OSHA testing protocols on a human model (change in fit factor, —77.4%; p-value, 0.0002). Nevertheless, whether the decontamination works through all the layers of trapped virus in the particles is unanswered and imperative to know before ensuring the reprocessing of COVID-waste.

In order to draw a realistic impact of disinfection technologies, a summative strength, weakness, opportunity, and threat (SWOT) analysis are presented in Table 1. As can be seen, pyrolysis is advantageous because of no known threat to the complete destruction of waste volume. On the other hand, vH₂O₂ and dry heat techniques have the opportunity for reprocessing of personal protective (PPE and N95 masks) and their re-use.

5. COVID-waste management strategies

Although COVID-waste management is in its early stage, the past experiences learned from the SARS, MERS-CoV, and Human immunodeficiency virus- Acquired immunodeficiency syndrome (HIV-AIDS) applied to the primary level along with the global learning of new ways to fight COVID-19 is imperative to re-visit. In this context, the policy briefs focus on South Korea, China, Spain, and India for COVID-waste management are discussed below.

5.1. Common safety measures on disinfection process

COVID-waste can play a vital role to spread hospital-acquired infections. However, several safety aspects are necessarily required to follow as a part of overall COVID-waste management (Yang et al., 2020). Disinfectant containing 2 g/L chlorine should be sprayed four times daily in the surrounding environment, floor, tables, and beds of the contaminated/isolated area and hospitals for a minimum of 30 min. The area/food contaminated with patient vomitus, blood, and secretions (also taken as COVID-waste), the same disinfection technique must be followed after the collection of COVID-waste in double-layered tightly closed yellow bags. All the clothes, bedsheets, and beddings used by COVID-19 patients including the gadgets used (like mobile phones, credit cards, glasses, etc.) require to be sprayed with 75% ethyl alcohol (C₂H₅OH). Safety guidelines for the use and discard of protective measures should be drawn including the sequence of wearing follows white coats, N95 facial masks, surgical masks, surgical hats, protective goggles, shoe covers, isolation gowns, gloves, protective suits, another pair of gloves, protective hoods, and boot covers. At the time of removing the protection wearing, spray of ethyl alcohol in the buffer room is the primary disinfection measure, thereafter, they can be allowed to take off the first layer of gloves and put on new gloves to take off the hood, PPE, goggles, and surgical mask sequentially in another room. Further, the removal of isolation gown, surgical hat, N95 face mask, gloves should be done sequentially in a semi-contaminated room. Then only, the healthcare person can be allowed to enter the clean area after hand sanitization and wearing of a clean surgical mask. All the used items collected in this process must be collected as COVID-waste (even after disinfectant spray) and processed for the next stage of treatment like incineration/microwave (as defined in Section 4).

5.2. Cradle-to-grave COVID-waste management in South Korea

Soon after the first outbreak of COVID-19 in South Korea, the Ministry of Environment tightened the existing “Wastes Control Act” by introducing “The Extraordinary Measures for Safe Waste Management against COVID-19” on January 28, 2020 (MOE-ROK, 2020a, 2020b). As per the new guidelines, COVID-waste cannot be stored more than 24 h and must be incinerated on the same day of collection; whereas, the earlier act was giving 7 days of storage time that can be incinerated within 2 days of delivery. Under the extraordinary measures for COVID-
waste, the household waste generated by self-quarantined persons would also be treated as COVID-waste (ESCAP, 2020). The guidelines re-visited after raising the health alert to level 4 (on February 23, 2020) state that the waste generated by the home-quarantine patients would be stored in dedicated bags and containers after the disinfectant spray. If the patient has been found COVID-19 positive, the stored waste must be kept close in the resin box (as the schematic is depicted in Fig. 4a). To treat the collected waste on a priority basis (within 24 h), the local waste disposal facilities have been directed to first treat the medical waste generated by home-quarantine patients over other municipal waste. In this work, helps from the private waste collection parties has been asked by distributing over 84,000 sets of PPE and masks to the workers involved in this task (ESCAP, 2020).

Until the mid of July, more than 2600 tons of medical waste were collected from 91 designated COVID-hospitals, 8 residential centers, 24 temporary facilities, and self-quarantine households that was disposed of by incineration on a priority basis. Not only the COVID-waste generated by the hospitals, health centers, and self-quarantines, but the waste generated during the disinfection of public area or, where an infected person visited have been directed to treat as medical waste and collection of those waste in double-packed designated bags are mandatory before sending to burning at the high-temperature incinerator facility. The waste generated by the health workers and medical waste inspectors of COVID-19 also designated as the same for a separate treatment.

The prompt, flexible, and pointed actions to handle the COVID-waste by the South Korean government could avoid critical situations without any severe safety issues and viruses spread by medical waste. Close monitoring of the quantity of COVID-waste generation from home-quarantine, designated hospitals and healthcare centers have been found helpful to track their disposal and treatment within a fixed time period of 24 h. Intensive inspections by the local environmental agencies could ensure the strict following of disposal guidelines in designated bags and containers. Moreover, a cooperation system developed for COVID-waste management as depicted in Fig. 4b could potentially contribute to drawing a simple decision-making process (MOE-ROK, 2020a, 2020b). The systematic and prioritized cooperation between the concerned agencies under the command of Central headquarter of disaster and control of the Ministry of Environment and local governments are found to be helpful for tackling the challenges effectively.

5.3. On-site treatment of COVID-waste in China

In the country of the first outbreak of COVID-19, the generated healthcare and bio-medical waste has overlapped the waste treatment facilities of China. The dreadful situation that arose due to COVID-waste can be understood by the fact that the inadequate capacity to treat BMW has been a long-standing issue in China. As per the record in 2018, China produced more than 200 million tons of BMW, however, 76 cities were unable to a timely waste treatment (Zuo, 2020). The exact volume of COVID-waste in the country is yet to be known; however, a known number of people infected (~0.1 million) and the generation of BMW (240 tons/day, a six-folds higher than earlier of COVID-19 outbreak) at Wuhan (Cutler, 2020) and ~200 kg of discarded facemasks collected alone from the bins of Wuhan’s Economic Development Zone clearly narrates the situation (Jiangtao and Zheng, 2020). To minimize the risk of infection, therefore, bigger space in outer area of hospitals (usually in the parking space) has been temporarily allotted for the storage, disinfectant spraying, and their smooth transportation to the treatment facility (CGTN, 2020).

According to the Ministry of Ecology and Environment’s emergency office, China has planned that every prefecture-level city should have a centralized medical waste treatment facility by the end of 2020 (Jing, 2020). It is noteworthy to mention that China has announced a “10-day battle” plan to test all 11 million residents of Wuhan for the novel COVID-19 (Wee and Wang, 2020). Such an ambitious drive will obviously generate a large amount of BMW. It is also reported that in lacking adequate waste treatment facilities, the COVID-waste of Wuhan was also carried to nearby cities facility like the treatment plants in Xiayang. The shortage of staff during the lockdown period and the high risk of cross-infection made this practice a highly-dangerous. Help asked from BMW management companies across the country offered the mobile waste treatment stations along with the plan to convert industrial waste disposal plants into BMW treatment facilities due to no industrial activity during the lockdown period. One of such mobile treatment facilities developed like Sterilwave SW440 with a capacity of up to 80 kg/h is depicted in Fig. 5 (BMW, 2020; Resilient Environmental Solutions, 2020). The capacity build-up with on-site mobile disposal of waste can greatly help to tackle the infectious waste but the capacity limits without any information on the health adversity and emission standards are the bottlenecks of this practice (CGTN, 2020).

| Table 1 | The summative SWOT analysis of each disinfection technology. |
|---------|-------------------------------------------------|
| **Disinfection technology** | **Strengths** | **Weaknesses** | **Opportunities** | **Threats** | **References** |
| Incineration technique | Simple operation, complete destruction of BMW/Covid-waste | Energy-intensive, high capex, release of toxins and solid residual waste | ~90% reduction of waste volume | Release of secondary pollutants like dioxin, furan, and bottom ash | Datta et al., 2018; Wang et al., 2020 |
| Pyrolysis technique | Complete destruction of toxins like furan and dioxins | High investment costs and strict demand for heat value of wastes | Energy saving and complete decomposition of waste volume | Not known and taken as a safe technology | Datta et al., 2018; Wang et al., 2020 |
| Microwave technique | Low air temperature saves energy, less pollutant release without gaseous emission | Relative narrow spectrum of disinfection, sometimes needs to be applied with autoclaving | Building of mobile microwave treatment facility is attractive to on-site waste treatment | Complex impact factors of disinfection | Datta et al., 2018; Wang et al., 2020 |
| Chemical technique | Rapid and stable performance, broad sterilization spectrum | Does not reduce volume and mass of BMW | In-house/on-site application of disinfectants potentially destroy virus spores thus effectively controls virus spread | Anthropic aerosols formed can penetrate alveoli upon inhalation, absorbance of atomized disinfectants into skin causes cancer | Mallapur, 2020; Rowan and Lafey, 2020; Singh et al., 2020 |
| Vaporized hydrogen peroxide | Heat sensitive low temperature application | Concentration reduces in presence of cellulose materials | Reprocessing and reuse of protective items is possible after a complete disinfection | Atomized aerosols due to fogging causes severe health damage to alveoli, skins, and mucosa | Barcelo, 2020; McEvoy and Rowan, 2019 |
| Dry heat technique | Polymeric material compatibility with reprocessing possibility | Decontamination works through all the layers of trapped virus in the particles is unanswer | Reuse of N95 masks and PPE are possible that can mitigate the risk of supply-chain | Decontamination of all layers of trapped virus in particles is questionable | Price et al., 2020 |

**Table:** The summative SWOT analysis of each disinfection technology.
5.4. Resource utilization for efficient handling of COVID-waste in Catalonia (Spain)

Spain is one of such majorly affected countries who has gone through the terrifying experience caused by the infections of SARS-CoV-2. As on 14 July 2020, Spain has registered 255,953 COVID-19 cases with 28,406 deaths of the citizen (https://covid19.who.int/region/euro/country/es). On 26 March 2020, the country hit by 8271 new cases against the recovery of 1648 patients. Due to this, the country has generated an unexpected amount of COVID-waste, treatment of which has become the most challenging task with limited disposal facilities. The medical waste that includes surgical gloves, facemasks, davantals, and PPE has jumped a massive rise of 350%, as recorded by the Waste Agency of Catalonia in the mid of March 2020. Approximately, 1200 tons of COVID-waste is generated against the usual medical waste generation of 275 tons/month during normal days (ACRPPlus, 2020).

To facilitate the rapid and optimal treatment of the huge amount of infectious waste, the agency has implemented to reinforce the ordinary management by the three authorized plants. The incineration of part of the medical waste (the one considered as low risk) has been authorized in some recovery plants which are receiving waste from health centers

Fig. 4. Public guidelines for the handling of waste for self-quarantine and COVID-19 patients in South Korea [a]; The cooperation system of South Korea developed for the effective management of COVID-waste (modified and adapted from ESCAP, 2020) [b].
and converted hotels. The existing facilities of municipal waste treatment like incinerators have put on the job to a priority disposal of medical waste. Although it took a long time, about 700 tons of medical waste out of 1200 tons could be treated until 15 April 2020 in Catalonia by using the facilities of municipal waste incinerators (ACRPlus, 2020).

As per the report surfaced by the Association of Cities and Regions for Sustainable Resource Management, the most challenging job remains in the segregation of COVID-waste from the municipal/household solid waste, in particular, the waste generated by the household self-quarantined people. Looking at the difficulties and the limited facilities with lacking clear guidelines during the initial outbreak, the situation has been observed not to be as good as South Korea. However, looking at the sudden attack of COVID-19 with lively countries of Europe like Spain their response to tackling COVID-waste cannot be neglected. The schematic summary of the waste management strategy including the COVID-waste after the outbreak in March 2020 is depicted in Fig. 6.

It can be seen that the collection of COVID-waste is directed along with the MSW, however, the instruction is very clear to double-seal the waste-containing bags and to keep it separate by the home-quarantine persons themselves and do not mix with common household waste (ACRPlus, 2020). The main drawback of this system has been found in the long-waiting time for sending it to the final disposal to incineration. A prolong waiting up to 72 h can be dangerous due to the long persistence of SARS-CoV-2 on different surfaces (Chin et al., 2020; van Doremalen et al., 2020); hence, there is every chance of cross-contamination within the gap period of COVID-waste generation and sending it to the automated incinerator facility.

5.5. Identification and isolation of COVID-waste for a safer treatment in India

Although no specific guideline was issued for handling COVID-waste up to mid of March 2020, as COVID-19 spread in India, a proper COVID-waste management system was introduced. It was imperative due to the fact that before this pandemic outbreak only 265 tons/day were undergoing to the treatment facilities out of the generated volume of 463 tons/day BMW (DNA, 2020). The first big step was to enact the Epidemic Disease Act, 1897; by which, the Central Government of India could directly impose its directives to the state governments. Then, the Central Pollution Control Board (CPCB) under the Ministry of Environment, Forest & Climate Change issued the specific guidelines on 18 March 2020 (CPCB, 2020a). The “Guidelines for handling, treatment,
and disposal of waste generated during treatment/diagnosis/quarantine of COVID-19 patients was issued to deal COVID-waste disposal at healthcare facilities including the quarantine camps, home-care, sample collection centers, testing labs, state pollution control boards, and bio-waste treatment facilities (CPCB, 2020a, 2020b, 2020c). Despite having the biomedical Waste Management Rule 2016, the guidelines kept specific to ensure COVID-waste disposal in a scientific manner (Aggarwal, 2020). The guidelines released by CPCB are summarized in Table 2. The guidelines suggest that the commonly used facemasks and gloves by general people for preventive measures should be enveloped for a minimum of 72 h before disposal as the MSW. It is emphasized that COVID-waste generated by the isolation wards must be kept in a double-layered dedicated yellow bags to collect and store separately by marking “COVID-19 waste” for a priority handling by the common bio-medical waste treatment facility, CBWTF (The Print, 2020).

CPCB has also given adequate directions and advisories even to the state pollution control boards (SPCB) who are responsible to implement CPCB’s guidelines on the floor. SPCB is authorized to maintain all the records related to COVID-waste generation, treatment, and disposal. This is also valid to tackle the BMW other than COVID-waste. SPCB can allow the treatment facility to run for extra hours, as and when required. In the revised guidelines of CPCB (issued on April 18, 2020), the operation of CBWTF and its associated staff are included as an essential service part of health infrastructure (The Hindu, 2020; SCCI, 2020).

### 6. Recommendations

It is clear that the threat of COVID-waste is higher than usual BMW. A serious and timely collection, treatment, and disposal of COVID-waste by following the full safety measures are the key to handle this infectious waste of high risk. Separate collection in double-seal designated bags/bins must be practiced by the isolation wards/hospitals/quarantine centers/home-quarantines. For a timely collection and disposal, the role of urban local bodies is quite important albeit in the lockdown period many waste treatment facilities are facing the manpower crisis. Therefore, the workers involved in this job must be taken as a part of an essential service. The proper healthcare and safety measures must be the responsibility of local bodies and the CBWTF operators. It is recommended that no COVID-waste should be disposed of by mixing with household solid waste and kept inside the closed container/bins. Not only the human-to-human contact but exposures with other potential carriers like mobile phones, keyboards, etc. should also be avoided. Moreover, the vehicles involved in COVID-waste collections must be disinfected by spraying a 1% sodium hypochlorite solution after every round of waste collection. Soon after the removal of PPE and facemasks, the workers should avoid touching their face, nose, mouth, and eyes; only after using a 70% alcohol sanitizer. The awareness among the people can be a panacea for safer handling of COVID-waste, hence, the government, local bodies, waste treatment facilities must drive the awareness program using different media to directly reach out to the people. The common use of surgical facemask and hand gloves is being largely consumed and due to their size and lightweight, there is every chance that these waste may be disposed of with solid waste. It is recommended to carefully deal with such waste as they can be highly infectious for a prolonged duration of 7 days. Hence, the guidelines to keep paper packing of the waste masks for a minimum of 72 h must be followed as the “prevention is better than cure”. In lower down the threat of SARS-CoV-2 by using COVID-waste fomites, their release to environment by the host, and persist on carrier surfaces highlights the multitude of the applied researcher that requires to address the effective control of pandemic outbreak due to the enveloped novel coronavirus (Wigginton and Boehm, 2020). Henceforth, an integral approach by environmental engineers, medical doctors, healthcare workers, and scientists can apply their unique skills and experiences with interdisciplinary research to address the need of the hour. For example, the disinfectant spray (H2O2/NaOCl) is commonly suggested to inactivate the enveloped virus from the waste surface (Gallandat et al., 2017), but this cannot work in each of the cases. The presence of blood on fomites would require a much higher dosage of disinfectant (Wood et al., 2020) that can be better understood for several other circumstances by interdisciplinary researches.

Due to the global shortcomings in supply chain of personal protective, reprocessing can significantly mitigate their shortage by other than impromptu recycling techniques. As reprocessing technology will

### Table 2

Central Pollution Control Board’s guidelines for COVID-waste management in India (CPCB, 2020a, 2020b, 2020c).

| Direction to sample collection centers and testing labs | Guidelines for the handling of COVID-waste |
|--------------------------------------------------------|------------------------------------------|
| COVID-19 isolation wards | • Use of separate color bins/bags in wards and maintain proper segregation of waste as per the BMWM Rules 2016. |
|                         | • Use of double-layer yellow color waste in the case of COVID-waste |
|                         | • Storage of the collected COVID-waste in a dedicated collection bin labelled as “COVID-19” after the disinfectant spray (1% NaOCl solution) on inner and outer surface of bags. |
|                         | • In addition, the COVID-waste must be labelled as “COVID-19 waste” to ensure the priority disposal at the treatment sites. |
|                         | • General waste other than COVID-waste should not be mixed and their disposal should be done as common solid waste. |
|                         | • Separate record for COVID-waste generation from the isolation wards |
|                         | • Deputation of separate collection staffs for COVID-waste and other solid waste to ensure the timely collection disposal of waste |
|                         | • Waste generation, collection, and treatment records tracking by SPCBs |
| Sample collection centers and testing labs | • Reporting of the collection centers and testing labs by the state pollution control boards to monitor the COVID-waste records |
|                         | • All the guidelines for isolation wards should be applied to the sample collection centers and testing labs |
| Quarantine camps and home-care of COVID-19 patients | • Treatment of common collected waste (non--medical) as solid waste |
|                         | • Separate collection of BMW if any in the yellow color bags/bins |
|                         | • As and when the BMW is generated, the quarantine camps must inform to the operator of CBWTF for the timely collection of COVID--waste |
|                         | • The waste generated by self/home-quarantine suspects/patient should be separately collected in yellow bags and handed over to the authorized collectors engaged by the local bodies |
|                         | • Reporting to the respective SPCBs about receiving of COVID-waste from isolation wards, quarantine centers and homes, and testing centers |
| Common biomedical waste treatment facility | • Regular sanitization of waste collectors |
|                         | • Providing the PPE, nitrile gloves, three-layer masks, splash proof aprons, safety boots and goggles |
|                         | • Use dedicated vehicle for COVID-waste collection with marking and essential sanitization of vehicles with 1% sodium hypochlorite |
|                         | • Immediate disposal of COVID-waste soon after the receiving |
|                         | • Operator of the facility must maintain separate record for collection, treatment, and disposal of COVID-waste |
|                         | • In case of worker showing illness symptoms, adequate leave should be provided to the worker without cutting the salary |
not only help to lower the virus spread and environmental benignness but also increase the availability of personal protective by their possible re-use. \(\text{H}_2\text{O}_2\) and hot air disinfection process has potential to apply for the reprocessing of COVID-waste, however, timely overcome from existing limitations like reduction in oxidant concentration in the presence of specific materials and degree of decontamination in all layers of the trapped viruses are desirable. On that basis, the imperative need for an integrated approach involving environmental engineers, healthcare workers, and researchers are being recommended overcoming the challenges of COVID-waste management.

7. Conclusions

The potential spread of SARS-CoV-2 through fomites of COVID-waste is not ruled out. In fact, the novel coronavirus can survive for long periods outside of its host organism like 72 h on the surface of a surgical mask. Hence, COVID-waste may cause to the community spread if handled inappropriately. The chemical disinfection using a 1\% \(\text{NaOCl}\) solution is one of the best in-situ practices which is also easy to spray and not limited to COVID-waste but it is also effective to sanitize the larger space, shopping malls, hospital premises/wards, and isolation centers. Microwave disinfection technique is useful to sanitize PPE and cloths that can be recylced and reused; whereas, incineration is useful to tackle a larger volume of COVID-waste which is an energy-intensive process but reliable process due to a high operating temperature (800–1200 °C). The strategy like “identify, isolate, disinfect, and safe treatment practices” has been found to be effective for safer management of COVID-waste. The on-site treatment of COVID-waste as per the China model to control the infection spread is attractive, however, the limited capacity is a big hurdle along with no proven record on emissions. The management practice of Catalonia (Spain) shows that the efficient management of existing resources can be helpful to deal with the challenges posed by COVID-waste. Public participation in the separate and timely collection of COVID-waste along with a priority disposal of the waste volume are the key factors to the effective management of an emerged category of BMW. The practices discussed herein will greatly help the strategy development for preventing/controlling the pandemic of similar episodes in the future.

CRediT authorship contribution statement

S. Ilyas: Conceptualization, Literature survey, Data curation, Funding acquisition, Writing – original draft, Writing – review & editing. R.R. Srivastava: Conceptualization, Hypothesis build-up, Literature survey, Writing – original draft, Writing - review & editing. H. Kim: Supervision, Funding acquisition, Project administration, Resources, Writing - review & editing.

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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