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Repercussions of COVID-19 pandemic on municipal solid waste management: Challenges and opportunities

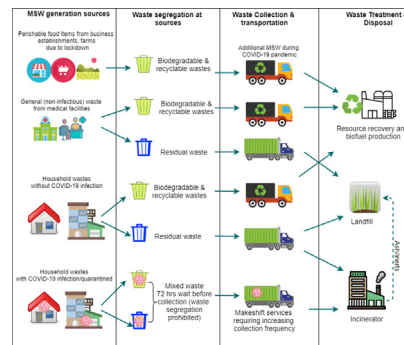
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HIGHLIGHTS

- Consequences of COVID-19 pandemic on municipal solid waste management are presented.
- Excess medical and household waste generated affects municipal waste management.
- Waste collection, recycling, treatment, and disposal become indispensable services.
- Pandemic proffers opportunities to establish sustainable waste management system.

GRAPHICAL ABSTRACT



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ABSTRACT

The COVID-19 pandemic has caused global emergency and has raised social and economic concerns which will also spill over to environmental issues. Amid this natural experiment, current study evaluates prevailing municipal solid waste (MSW) management practices, with the emphasis on MSW treatment and disposal facilities in select developed and developing countries. The data and information used in this paper is collected from several scientific research papers from different disciplines, publications from governments and multilateral agencies and media reports. Despite limited literature on MSW management during such pandemics, this article presets a global backdrop of MSW management during COVID-19 outbreak and examines various aspects of MSW management. Discussion includes identifying parameters of disease transmission through solid waste handling, consequences of medical waste surge on current municipal waste treatment and disposal systems. Further, based on previous pandemic and disaster waste management studies, this study also presents challenges and opportunities in the aftermath of the ongoing pandemic. The paper recommends alternatives approaches for MSW treatment and disposal and outlines the future scope of work to achieve sustainable waste management during and aftermath of the pandemics.

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1. Introduction

Following the severe acute respiratory syndrome coronavirus (SARS-Cov-1) outbreak in 2002 and the Middle East respiratory syndrome coronavirus (MERS-CoV) outbreak in 2012, SARS-CoV-2 disease

has become the third coronavirus to emerge in the past two decades (Wang et al., 2020). At the time of writing this article, total number of confirmed positive cases of coronavirus disease 2019 (COVID-19) was 3,677,165 worldwide (Johns Hopkins University Coronavirus Resource Centre, 2020). Millions of people have been put under lockdown across the globe in order to reduce the transmission of virus (Saadat et al., 2020). In response to coronavirus pandemic, countries have instituted economic recovery programs to alleviate unemployment. Whilst it is

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understandably difficult to contemplate other adverse consequences in the midst of this pandemic, it is vital to remember that there is another major challenge that threatens human prosperity-climate change. Leveraging COVID-19 recovery programs to simultaneously facilitate the climate agenda presents a strategic opportunity to transition towards a more sustainable post-COVID-19 world (Rosenbloom and Markard, 2020).

The pandemic has posed major environmental challenges including municipal solid waste (MSW) and hazardous biomedical waste management. Solid waste association of North America (SWANA) has reported potential changes in the volume and source of solid waste generated due to enforcement of lockdown by the authorities to contain the disease outbreak (SWANA, 2020). China, from where the COVID-19 infection started, the government has recorded the relevant data on this issue. According to the 11 March press releases of the State Council's joint prevention and control mechanism in China, the amount of MSW in large and medium sized cities was reduced by 30.00% during the disease outbreak. However, the generation of medical waste (infectious and noninfectious) increased sharply (+370.00%) in Hubei Province (Klemes et al., 2020). World health organization (WHO) has formulated guidelines for the disposal of infectious and noninfectious healthcare waste during COVID-19 outbreak. The proportion of noninfectious waste, which is more than 80.00% of the total quantity of healthcare waste generated, needs to be collected and disposed as municipal waste (WHO, 2020).

Among many unprecedented impacts of the current pandemic, municipal waste management practices are expected to gain more concerns as time passes by (Smart Waste Report European Union, 2020). WHO has suggested that the waste treatment and disposal procedures in healthcare facilities should consider controlled conditions of thermal treatment or use of traditional biocidal agents that are effective in destroying coronavirus (Kampf et al., 2020). However MSW management outside the healthcare facility needs to be addressed, considering factors such as virus resistance, differences in waste management systems and the climatic conditions in each of the affected region (Mol and Caldas, 2020). Otherwise we may risk further spread of the coronavirus mainly in developing countries due to poor waste handling conditions associated with inappropriate use of personal protective equipment and other unfavorable conditions (Mol and Caldas, 2020).

Only a few studies have reported on MSW management during COVID-19 pandemic. Klemes et al. (2020) have investigated the short-term and long-term changes in plastic waste management practices due to the disruption caused by COVID-19. The study focuses on plastic waste management and provides some insights on MSW handling. Study conducted by Nghiem et al. (2020) evaluated the consequences of COVID-19 outbreak on waste and wastewater service sectors. The work underlines the potential risk of disease transmission through the non-hazardous waste from healthcare facilities (Nghiem et al., 2020). Zambrano-Monserrate et al. (2020) have reviewed the positive and negative effects of pandemic on the environment; this study highlights concerns such as, increase in volume of the healthcare waste and delay in waste recycling activities, which may negatively affect the environment. Saadat et al. (2020) have also discussed environmental perspectives and socioeconomic aspects of the COVID-19 outbreak. Solid waste management related studies are scattered across different disciplines (e.g. environmental science, disaster operations management and management science) (Zhang et al., 2019). As a result, there is a need for detailed study which evaluates different aspects of MSW management during pandemics and provides a backdrop for the further research on this topic. The present study reviews MSW management practices in few of the developed as well as developing countries during COVID-19 pandemic, which is considered as a global natural experiment (Thompson, 2020). The analysis focuses on various types of waste generated during the COVID-19 outbreak that impact the existing MSW management practices. The work highlights potential risks of SARS-CoV-2 transmission in these practices and also presents a few risk-

mitigating approaches to MSW management such as decentralized waste management and its integration with existing system. The study also contributes to the existing literature by evaluating the governments' responses in developed and developing countries to the increased burden on MSW management systems due to pandemic.

The remainder of this paper is structured as follows. In Section 2 we present the prevailing practices of MSW management during COVID-19 pandemic across both developed and developing countries. This is followed by a section on the factors that could potentially influence SARS-CoV-2 transmission via MSW handling. The ramifications of this pandemic on existing MSW management systems are discussed in Section 4. Our analysis suggests that there is scope for improving the entire MSW management lifecycle, from waste collection to disposal. We highlight these opportunities for improvement in Section 5. Finally, in Section 6 we present the conclusions and scope for future work of our study.

2. Global practices in MSW management during COVID-19 pandemic

2.1. Municipal waste generation and governments' responses

The COVID-19 crisis has affected the industry on several fronts (Kahlert and Bening, 2020). For instance, food producers in the United States suffered due to the closure of schools, restaurants, and other institutions that normally purchased large food quantities. A significant amount of food waste was generated during initial lockdown period (Waste360, n.d.; <https://www.waste360.com/food-waste/new-challenges-and-solutions-food-waste-during-covid-19-pandemic>). The United States Environmental Protection Agency (US EPA) responded by releasing guidelines for recycling and sustainable management of food waste during COVID-19 public health emergency. These guidelines address food waste management at households, institutions and business levels (US EPA, 2020). In India, countrywide lockdown coincided with the country's peak harvesting time of a variety of seasonal crops. Summer vegetables and fruits were ripe and ready to pick; wheat, paddy and barley crops were also ready for harvest. However, due to the sudden lockdown in the country, most of the produce was wasted (FAO, 2020). In addition to announcing economic stimulus plan, the government of India also undertook measures to counter wastage of perishable products. Food inspectors were involved to ensure disbursement of food items to restaurants, grocery establishments, and the affected people. Importantly, technological interventions such as food delivery applications enabled the government to reach the localized and remote individuals ensuring efficient food management and reduce the food wastage (FAO, 2020).

The volume of waste and recyclables generated from the residences during COVID-19 outbreak has increased. SWANA estimated in late April that, the residential waste volume in the United States peaked nationally at about 20.00% higher than normal, with some localities experiencing an increase of more than 30.00%. Because residential waste and recyclable volumes spiked higher, some local governments temporarily suspended their curbside recycling collection programs to ensure that all of the trash was collected and managed efficiently (SWANA, 2020). While the volume of curbside mixed waste has increased, return levels in waste deposit systems have temporarily fallen due to limited mobility and fear of contagion among the residents (Kahlert and Bening, 2020). Furthermore, due to lockdowns, the industrial activity also declined substantially across countries (United Nations Industrial Development Organization, 2020). This decline in industrial production has significantly reduced the supply of high-value material from post-industrial waste (Kahlert and Bening, 2020).

Current coronavirus pandemic is posing challenges to municipal waste management practices and procedures such as safety and health measures for employees, waste treatment requirements, general procedures due to coronavirus for waste sector (ACRPlus, 2020). Governments have identified the importance of MSW management during

the disease outbreak and have undertaken various measures to tackle the situation. For instance, to avoid burden on municipal waste system during this pandemic, citizens in Austria are asked to reduce waste generation and segregate waste as best as possible. During the initial stage of the outbreak, guidelines were articulated for the citizens to effectively carry out waste reduction and segregation, without compromising on the individuals' health and safety (Land Oberösterreich, 2020). Tokyo has reported an increase in the household combustible waste by 3.10% due to rise in the number of people eating and drinking at home (The Japan Times, 2020). The British government has published COVID-19 regulatory position statements for local authorities and waste collectors. These statements focus on waste stream prioritization, expansion in the temporary waste storage capacity, waste segregation, adaptation of MSW incinerator to process COVID-19 infectious waste, and communication with residents (DEFRA Government of UK, 2020a).

European Commission has formulated a guidance document for waste management in the context of coronavirus crisis. The document emphasizes on an overall continuity of proper MSW management services, including separate collection and recycling in accordance with EU law. It further specifies that if the services were to be reduced, the continuity and sufficient frequency of collection of residual and biodegradable waste has to be ensured for the final disposal (European Commission, 2020). The US occupational safety and health administration (OSHA) has pre-defined safety guidelines for personnel involved in MSW management. In response of COVID-19 crisis, OSHA recognized MSW management as an essential service and it has mandated personnel involved in MSW management to implement those precautions (OSHA, the government of US, 2020; Liu et al., 2020). Developing countries like India, Vietnam, and Malaysia have published guidelines for the handling of medical waste and waste generated in infected households. However, little attention has been paid to the management of MSW. Municipal waste management is an essential and routine service which is indispensable. Services of MSW management play a key role in mitigating infectious disease transmission but are rarely mentioned in public health crises response communication (Nghiem et al., 2020).

2.2. Pre-pandemic MSW treatment and disposal practices in developed and developing countries

Even before COVID-19 outbreak developed countries had established municipal waste treatment and disposal facilities. To illustrate, in Japan, 74.00% of MSW generated is incinerated, 17.00% recycled and 3.00% of the waste is disposed in landfills (Mollica and Balestieri, 2020). Countries such as Sweden, Denmark, Finland and Norway incinerate more than 50.00% of their MSW with energy recovery system (Istrate et al., 2020). Austria is handling its MSW through composting (32.00% of waste generated), incineration with energy recovery facility (40.00%) and less than 9.00% of the waste is sent to landfills (Kyriakis et al., 2019). In 2018, the UK recycled 45.00% of the waste from households and 20.00% of the biodegradable fraction of MSW was landfilled. By 2016, there were 78 incineration facilities with the energy recovery system with the capacity of 8.474 million tonnes per year (DEFRA Government of UK, 2020b). Treatment and disposal of MSW generated in the US involves, recycling (25.10%), composting (10.10%) and combustion with energy recovery (12.70%). Unlike other developed countries, more than 50.00% of the total MSW generated in the US is landfilled (US Environmental Protection Agency, 2017). Changes implemented in MSW management services during COVID-19 pandemic in developed countries like the UK, the US, Singapore, Japan and Europe is depicted in Fig. 1. In comparison, the MSW management services during COVID-19 pandemic in developing nations like India, Malaysia, Brazil, Indonesia and Vietnam are represented in Fig. 2. In both Figs. 1 and 2, the term residual waste refers to that waste which cannot be beneficially recycled or reused for economic, environmental or practical reasons (DEFRA Government of UK, 2014).

Major proportion of the MSW generated in countries like Indonesia, Brazil, China and India is disposed in landfills and dump sites. A study conducted to estimate greenhouse gas emissions from MSW in Indonesia has reported that 60.00 to 70.00% of the generated waste is transported to landfills, while the remaining 30.00 to 40.00% ends up in rivers, burned or independently managed by the community (Kristanto and Koven, 2019). A comparative analysis of energy and economics in generating electrical energy from urban solid waste in Brazil reported that 58.70% of the urban solid waste produced was disposed in sanitary landfills (Santos et al., 2019). A review study of environmental sustainability assessment of MSW land disposal for Indian cities estimated that more than 70.00% of the waste generated in cities is land disposed (Kulkarni, 2020). In populous countries like China, incineration is the most widely used WtE option (Kumar and Samadder, 2017). Istrate et al. (2020) reported that MSW incineration capacity in China increased from 15,000 t per day in 2003 to 231,600 t per day by 2015, however, significant portion of MSW is still disposed in landfills.

3. Factors influencing the SARS-CoV-2 transmission through MSW handling

Barring the biological and physiological factors of virus, there are other crucial factors like social and urban fundamentals of the transmission of COVID-19 which influence the outbreaks to a large scale (Liu et al., 2020). The survival time of the SARS-CoV-2 virus on different material surfaces is vital to decide the disinfection and precautionary measures for personnel handling such materials (Kampf et al., 2020). Hence these parameters may affect the spread of the infection in urban areas and similar set ups through inadequate management of MSW.

3.1. Survival time of the virus on surfaces

Transmission of the COVID-19 virus is possible through two channels- respiratory and contacts (WHO, 2020). Respiratory droplets are generated when an infected person coughs or sneezes. Apart from human to human transmissions, droplets may also land on surfaces where the virus could remain viable; thus, the immediate environment of an infected individual can serve as a source of transmission (WHO, 2020). Warnes et al. (2015) examined the persistence of infectious human coronavirus on common surface materials by applying 20 µl infected-cell lysate to 1 cm² coupons of test surface materials, which were incubated at ambient conditions; temperature 21 °C and relative humidity 30 to 40%. Virus was removed and assayed for infectivity at various time points (Warnes et al., 2015). Doremalen et al. (2020) conducted comparative analysis of survival time of SARS-CoV-1 and SARS-CoV-2 viruses in aerosols and on common surface materials. For surfaces, viruses were applied on the cardboard, steel, plastic and other test surfaces maintained at 21 to 23 °C and 40% relative humidity, the observation period was 7 days. For studying survival time in aerosols, viruses were aerosolized in a rotating drum maintained at 21 to 23 °C, 65% relative humidity and was observed over 3 h (Doremalen et al., 2020). Kampf et al. (2020) reviewed the survival time of coronaviruses on inanimate surfaces; the study observed that human coronaviruses can remain infectious on inanimate surfaces like metal, glass or plastic for up to 9 days (Kampf et al., 2020). The range of survival times estimated by these studies is presented in Fig. 3.

Li and Jenq (1993) and more recently Kalogiannidou et al. (2018) evaluated the physical composition of medical waste, and reported that apart from infectious waste, the general (noninfectious) waste from hospitals was mainly composed of materials like cardboard, plastic, latex rubber, textiles and synthetic materials. Kumar and Samadder (2017) have estimated that the inorganic fraction of MSW which mainly consists of plastic, rubber, metal and glass is approximately 54.00% for developed nations, whereas for developing countries

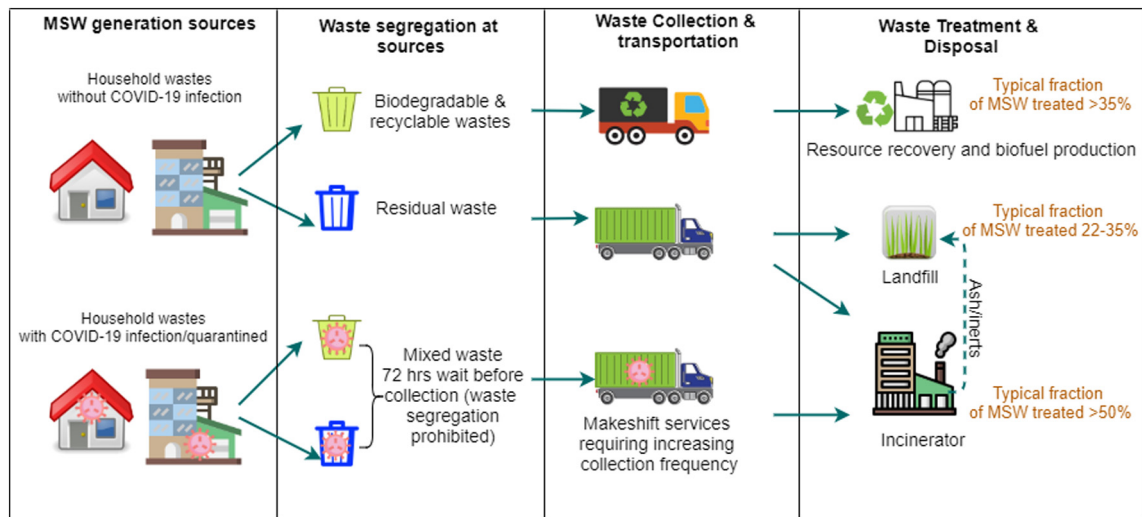


Fig. 1. MSW management in select developed countries during COVID-19 pandemic (ACRPlus, 2020; Nghiem et al., 2020).

it is 32.00%. This indicates that waste materials generated from households and quarantine facilities with the infected or suspected patients may contain possible SARS-Cov-2 and could be a source of infection for people outside the facility (Nghiem et al., 2020).

3.2. Population density

Population density is the number of people living in area per square kilometer (Priyadarsini and Suresh, 2020). During COVID-19 outbreak, presence of any potential source of infection on wastes collected from healthcare facilities and residential premises with COVID-19 positive cases will risk the health of personnel involved in waste management. COVID-19 spreads by droplets shed of the respiratory system by someone with the virus, which implies that it would spread with higher proximity of people, larger contact networks and lower levels of hygiene (Saadat et al., 2020). By reducing contact rates, the growth rate of the outbreak can be reduced. Controlling contact rates is a key to outbreak control, and such a strategy depends on population densities (Rocklov and Sjodin, 2020).

3.3. Socio economic conditions

The COVID-19 outbreak has not affected everyone in the same way (Saadat et al., 2020). Aparcana (2017) reviewed the role of informal sectors in management of MSW in low-income and middle-income countries; study noted a significant contribution of informal sector in waste recycling and material recovery in countries like Bangladesh, China, India, Mali, and Philippines. Informal sector in MSW management may refer to individuals, families and private micro-enterprises working in waste management services, whose activities are neither organized, sponsored, financed, contracted, recognized, taxed, nor reported by the government authorities (Paul et al., 2012).

The people involved in the informal sector waste recycling reside in the proximity of waste dump sites under the dire hygiene and sanitation conditions. The pandemic is predominantly detrimental to members of those social groups, including people living in poverty situations, aged people and individuals with disabilities. They are highly vulnerable to the outbreak. Early evidence indicates that the health and economic impacts of the virus are being borne disproportionately by poor people and

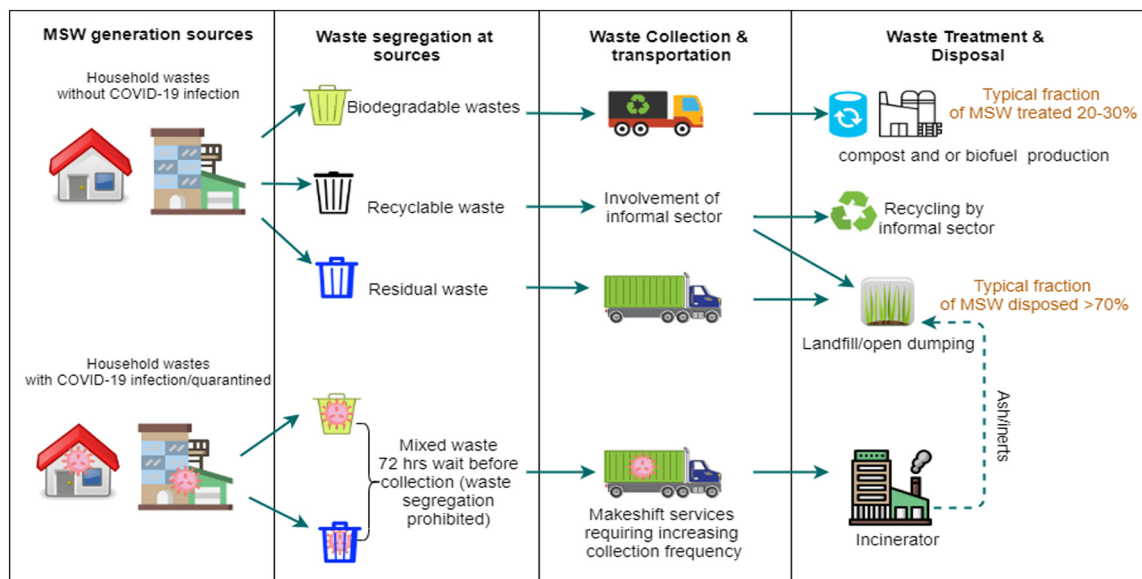


Fig. 2. MSW management in select developing countries during COVID-19 pandemic (ACRPlus, 2020; Nghiem et al., 2020).

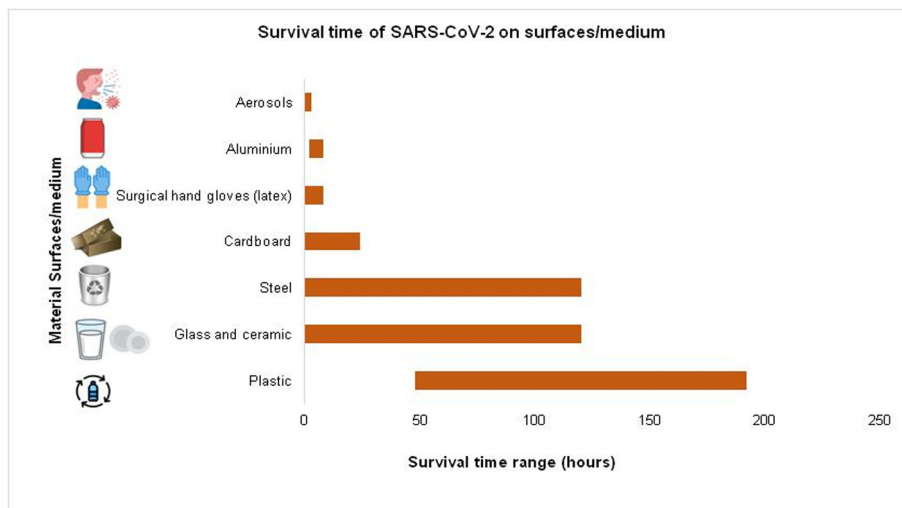


Fig. 3. Survival time of SARS-Cov-2 virus on different surfaces/medium (Doremalen et al., 2020; Kampf et al., 2020).

suffer inexplicably both from the pandemic and its aftermath, whether due to limited movement, fewer employment opportunities, increased xenophobia etc. (United Nations, 2020).

4. Ramifications of COVID-19 pandemic on MSW management system

4.1. Burden on MSW services due to surge in medical and household waste

Managing medical waste from hospitals is a demanding task as residual pathogens have to be destroyed prior to disposal (Klemes et al., 2020). These wastes are classified before their further processing; the typical composition of healthcare waste is approximately 85.00% general non-infectious, 10.00% infectious/hazardous and 5.00% chemical/radioactive (Wang et al., 2020). Treatment facilities are typically equipped to handle steady-state conditions where the medical waste is handled at a predictable average flowrate and composition. The choice of treatment is a function of economic, technical, environmental, and social acceptability. Rapid increase in waste volume is likely to upset systems that are designed for steady-state conditions (Klemes et al., 2020). Disposal of non-hazardous waste from healthcare facilities follows the typical solid waste management protocol (WHO, 2017). This has been the practice in several countries, for instance, India, in its guidelines to manage health care waste during COVID-19 pandemic, has recommended the disposal of general solid waste generated from medical facilities including households with positive COVID-19 cases as per the prevailing local method of disposing general solid waste (CPCB the Government of India, 2020). Medical waste generated in select Asian cities during this pandemic is presented in Table 1.

Table 1 shows the estimated volumes of medical waste generated based on the experience of China (Asian Development Bank, 2020). Based on the estimates from Table 1 it can be noted that during COVID-19 outbreak, cities collectively contributed around 864.00 tons of general medical waste to the MSW each day. Landfilling is still one of the most common MSW management option in Asian developing countries like India, Malaysia, Thailand, Bangladesh, Myanmar, and Indonesia (Kulkarni, 2020; Yadav and Samadder, 2018). The spread of COVID-19 may be increased by the inadequate waste management. With the rapid rise in the number of confirmed cases, the amount of COVID-19 related medical waste also increased significantly (Peng et al., 2020). Observing how the additional waste overwhelmed China's medical transport and disposal infrastructure, the Asian development bank has emphasized the need for additional waste

management infrastructure to reduce the further spread of COVID-19 and the emergence of other diseases.

Adding non-infectious medical waste to typical MSW generated increases the burden on existing MSW management system. The amount of waste overloads the existing treatment and disposal facilities, posing the risk of secondary contagion from inadequate waste management (Klemes et al., 2020). To handle the surge in waste amount, Spain has recommended that if necessary, cement plants can co-incinerate waste upon request. In Norway, the government has allowed temporary change in landfill permits (and permits to carry waste elsewhere) to cope with the medical waste surge (ACRPlus, 2020). Following the measures during circuit breaker period till 1 June 2020, Singapore's public waste collection services (PWCs) are facing manpower constraints, which have affected some of their collection schedules. The PWCs have made interim operational adjustments in some areas and selectively implemented alternate day collection of refuse at some landed premises and housing development board premises (National Environment Agency Singapore, 2020).

Countries have mitigated COVID-19 transmission through social distancing, self-quarantining, avoiding large gatherings, working from home, sending back students to their residences, providing online education, reduced travel, limiting visits to stores and many such activities have become routine during this pandemic (Sarkis et al., 2020). These measures have led consumers to increase their demand for online shopping for home delivery. Consequently, amount of biodegradable household waste has increased (Zambrano-Monserrate et al., 2020). This unprecedented situation presents significant challenges for the provision of waste collection, treatment and disposal of wastes (Nghiem et al., 2020).

4.2. Waste recycling

Waste recycling aims to optimize the use of different resources for the purpose of achieving more general profit and less waste production (Almasi et al., 2019). Recycling of domestic recyclable waste in most developed countries is part of the MSW management that is directly managed by government departments. The recycling is always operated by standardized, specialized enterprises; thus, in most developed countries recycling systems could be considered as formal systems. Nevertheless, for many developing countries that have relatively low economic and regulation level the treatment of MSW is not well developed (Fei et al., 2016). In an effort to continue MSW management services during COVID-19 outbreak developed countries have prioritized waste

Table 1
Estimated volume of medical waste in select Asian cities (Asian Development Bank, 2020).

City	Population (in millions)	Additional medical waste (t/d)	Total estimated production over 60 days in metric tons (mt)	Waste included in MSW channel (85% of the total estimate) (mt)
Manila	14.00	280	16,800	14,280
Jakarta	10.60	212	12,750	10,838
Kuala Lumpur	7.70	154	9240	7,854
Bangkok	10.50	210	12,600	10,710
Ha Noi	8.00	160	9600	8160

categories for collection and further processing. For example, the UK has defined high, medium, and low priority waste streams, and recyclable waste has been categorized as the medium and low priority categories which are collected once in a week/fortnight (DEFRA Government of UK, 2020a). A few cities in the USA have stopped recycling programs as authorities are concerned about the risk of COVID-19 spreading in recycling centers (Zambrano-Monserrate et al., 2020). Singapore has reduced the frequency of recyclable waste collection from the housing premises during circuit breaker period (National environmental agency, Singapore, 2020). The accumulated recyclable waste from households may act as potential source of infection if there are any suspected cases of COVID-19 in the proximity. Such waste poses threat to waste management personnel as well. Most of the European countries have prohibited waste segregation in corona virus infected households (ACRPlus, 2020).

Waste recycling in developing countries is driven by both formal and informal sectors, during the current coronavirus pandemic, while personnel involved in waste handling across the countries are protecting their communities, those in the informal sector face risk to their own health and livelihoods as countries lockdown and economies slow down (World Bank, 2020). The importance of implementing best management practices for waste handling and hygiene should be reemphasized to limit workers exposure to potentially contaminated waste (Nghiem et al., 2020).

5. Opportunities for sustainable MSW management in the aftermath of COVID-19

Crises are events where 'all bets are off' and the 'rules of the game' can be up for renegotiation and rewriting, where there are new openings for new ideas, practices and possibilities (Barry, 2020). The current coronavirus crisis tests the pre-pandemic municipal waste management system of the countries, underscores the lacunae and proffers opportunities to establish sustainable waste management system.

5.1. Waste collection and recycling

Due to social distancing protocols, lockdowns and prohibited entry in cities or provinces to contain the disease transmission, the movement of people is restricted and this affects routine waste collection. The mismatch between limited waste collection and surplus waste generation during pandemic exacerbates waste management activities. Waste treatment and recycling service is affected due to the waste stream prioritization for MSW management during COVID-19 crisis (Zambrano-Monserrate et al., 2020). Alternative approaches to alleviate burden on existing waste management system are required. One possible solution for uninterrupted waste management is integrating decentralized approach with the existing MSW management system. Decentralized waste management involves treatment and recycling of the waste in the vicinity of waste generation source. This reduces the burden on waste collection and transportation services, which can significantly reduce the risk of infection to personnel involved. Moreover, decentralized approach

can be implemented for select types of wastes at reduced investment and operating cost. Finally, the approach is easily adaptable to the existing waste management practices (Bhave and Kulkarni, 2019). Integration of different approaches for solid waste management optimizes the existing systems and implements new waste management systems. In addition to climate concern, the recycling and energy recovery enriches the resource efficiency and reduce the environmental impacts from greenhouse gas emission (Ramachandra et al., 2018). However, further study is required to assess the feasibility of incorporating decentralized systems in existing waste management system, during unprecedented events like COVID-19 outbreak.

5.2. Temporary waste storage and reduction site

The temporary waste storage and reduction site (TWSRS) is a place with specific logistic characteristics that allows to temporarily storing waste and debris, waiting for the final disposal. During the storage, it is possible to pre-treat waste, reducing the volume by grinding and screening (Gabrielli et al., 2018). For waste management during the natural or manmade disasters, the United States Federal emergency management agency (FEMA) recommends developing temporary waste storage and reduction sites between waste generation sites and final disposal sites. Temporary waste storage sites play multiple roles. Firstly, they can provide a buffer and space by hauling waste from the source of waste generation to the TWSRS. Secondly, operations such as sorting, shredding, and chipping can be done at the TWSRS to reduce the amount of waste as well as preparing for recycling. Finally, they can act as temporary storage places before the final disposal of waste (Cheng and Thompson, 2016). Selection of temporary storage sites and processing sites is crucial during emergency situations. This facilitates in allocating human resources and vehicles, storage of the waste as well as processing of them (Zhang et al., 2019). TWSRS selection criteria suggested in the literature include, length of storage time, real estate costs, site size and capacity, condition of waste materials, sites for designated materials, ease of accessibility, traffic condition, length of haul, truck size and equipment required (Cheng and Thompson, 2016). Moreover, it is important to know the origin and characteristics of the waste that are transported to temporary storage sites, in order to prevent problems like odour, noise and potential contamination (Gabrielli et al., 2018). For example, in the UK, to manage the additional waste generated during the COVID-19 pandemic, temporary waste storage capacity has been increased (DEFRA Government of UK, 2020a). Temporary waste storage and reduction sites equipped with waste pre-treatment facilities like grinding and screening on such locations will reduce the waste volume for the final treatment and disposal (Berger et al., 2011). Studies have assessed the viability of temporary waste storage, recycling and other aspects of waste management during disasters like earthquakes, floods, and hurricanes. However, the social, environmental and economic feasibility of such infrastructures during the pandemics need to be investigated to ensure sustainable waste management.

5.3. Alternative strategies for sustainable MSW management

One of the challenges during and aftermath of the COVID-19 outbreak is sound management of excess solid waste generated (UNEP, 2020). A possible solution for processing large quantum of waste is thermal treatment (waste to energy) with energy recovery facility. Studies have reported that volume reduction of 80.00 to 95.00% is achievable for generated waste by thermal conversion technologies (Singh et al., 2011; Kumar and Samadder, 2017; World Bank, 2018). Other advantages of modern day thermal treatment system include hygienisation (waste is decomposed at temperature > 850 °C), mineralization and immobilization of hazardous substances and resource conservations (Brunner and Rechberger, 2015). Mayer et al. (2019) assessed the waste to energy technologies implemented in developed and developing nations, they observe that developed countries have turned away from landfills, either due to environmental concerns or scarcity in the land area, and subsequently developed waste to energy technologies for waste management. However, in developing countries, depending on waste type, both recycling and recovery may demand an advanced plant design, medium to high engineering complexity and major capital costs (Mayer et al., 2019). Due to these reasons both options are often disregarded and major fraction of the waste generated is disposed in landfills and open dump sites. The study claims that the technologies like waste to energy are rarely utilized in developing countries (Mayer et al., 2019).

5.4. Revamping disaster waste management plan

Disaster waste management is always difficult, time-consuming, expensive (Zhang et al., 2019) and involves various stakeholders (Gabrielli et al., 2018). Existing disaster waste management planning mainly focuses on debris generated during natural disasters like earthquakes and floods. Optimization and decision-making tools are needed to support waste management planning: treatment approaches, infrastructure, automated treatment and collection design, logistics, safety and regulatory aspects link to the bio-disaster response (Klemes et al., 2020).

6. Conclusions and future outlook

Municipal solid waste management is an essential public health service, which requires immediate attention from authorities during and aftermath of the COVID-19 pandemic. Inadequate MSW management during such crisis poses potential risks to MSW handling personnel and amplifies virus transmission among the people. Hence there is a pressing need to evaluate different aspects of MSW management, in detail, during coronavirus outbreak. The present work reviewed MSW management practices in few of the developed as well as developing countries during COVID-19 pandemic, which is considered as a global natural experiment (Thompson, 2020). The analysis focused on various types of waste generated during the COVID-19 outbreak that impact the existing MSW management practices. The work highlighted potential risks of SARS-CoV-2 transmission in these practices and reported risk-mitigating approaches to MSW management such as decentralized waste management and its integration with existing system. The study also contributed to the existing literature by evaluating the governments' responses in some of the developed and developing countries to the increased burden on MSW management systems due to pandemic. Present study can be considered as a report on MSW management in the COVID-19 natural experiment.

This study provides groundwork for the further research in sustainable MSW management during COVID-19 outbreak. Further investigation is required to evaluate variations in waste characteristics and quantity of waste generation. These are the prerequisite conditions to develop effective waste treatment and disposal facilities. There is also an immediate need to evaluate economic, environmental and social

feasibility of integrating alternative approaches like decentralized systems with existing MSW management during public health emergencies. Role of temporary storage and reduction facilities in handling the excess waste, its economic repercussions, and availability of staff for the task during such outbreaks need to be assessed. To ensure uninterrupted MSW management services and safeguard personnel involved during lockdowns, role of automation in waste management needs to be explored. As the world adapts to unrivalled behavioral, societal, economic, and environmental changes to counter the risks posed by COVID-19 outbreak, public services and operations must also adapt and transform.

CRedit authorship contribution statement

Bhargavi N. Kulkarni: Writing - review & editing. **V. Anantharama:** Writing - review & editing.

Declaration of competing interest

The authors do not have any known conflict of interest either with any individual or institution.

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