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Implications of the COVID-19 Pandemic on the Management of Municipal Solid Waste and Medical Waste: A Comparative Review of Selected Countries

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Review

Implications of the COVID-19 Pandemic on the Management of Municipal Solid Waste and Medical Waste: A Comparative Review of Selected Countries

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Abstract: The COVID-19 outbreak has impacted many daily activities and services we depend on. Due to changes in waste quantity and types, solid waste management (SWM) services such as waste collection, transportation, and treatment/disposal suffered. Global rules and mandates were issued to address these changes and the COVID-19 pandemic. This mini review examines seven countries and summarises the pandemic's effects on municipal solid waste (MSW) and medical waste (MW) generation in terms of amount and composition, the SWM sector's challenges, and government or other SWM guidelines and management measures. The data are analysed to provide suggestions for stakeholders on SWM worker protection, waste segregation, and recycling. This article identified that extending MW incineration, separating infectious waste at the source, and discontinuing recycling for infection control are the best ways to manage solid waste. The waste management system's readiness was crucial to the pandemic response. Thus, countries like China, which has a robust SWM system, were able to contain the crisis and restrict danger, while others with weaker systems struggled. Additionally, the study highlights the importance of revising waste management policies and developing crisis response strategies that integrate flexible, innovative solutions to adapt quickly to changing waste demands and ensure public health and environmental protection during global health crises.

Keywords: COVID-19; solid waste management; medical waste; municipal solid waste; pandemic response; waste management policy

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1. Introduction

The outbreak of the coronavirus disease "COVID-19" pandemic in late 2019 is considered one of the hottest issues in the twenty-first century and has occupied a front seat in the agendas of all the countries around the world [1]. With all the governments making a great effort to flatten the curve of the virus spread, another curve must be flattened: the waste generation curve that can cause a massive disaster to the environment and human health [2]. An enormous number of medical wastes (MWs) were generated and will be generated in order to overcome the spread of COVID-19 in the form of tonnes of single-use plastics and disposable plastic-based personal protective equipment (PPE) such as face

masks, gloves, goggles, gowns, and aprons. The intense demand for PPEs has surged the production of these materials and caused wastage. The State Council of China found that COVID-19 is associated with approximately 470 tonnes of MW daily [3]. Generally, it is estimated that MW increased by 40% worldwide during the pandemic [4].

The disposal of MW is an unexpected overburden to the governments of developing countries, and it needs special treatment and safe disposal. The problem with COVID-19-associated wastes is that they cause an immediate threat that impacts the unsafe disposal of MW, resulting in a crisis of environmental pollution. Besides polluting the environment, another major problem caused by unsafe disposal is that it increases the spread of the virus. Throughout history, the leading cause involving the spread of infectious diseases such as HIV/AIDS, hepatitis, typhoid, and cholera has been the unsafe disposal of their associated MW [5]. These observations are observed in developing countries and their associated economies. Proper integrated solid waste management (SWM) is a top priority and primary concern in these countries where sustainable approaches are scarce, and the MW has not been effectively integrated [6].

The pandemic affected the MW and municipal solid waste (MSW) generation, composition, and flows [7]. Different trends in MSW can be observed in different countries, cities, and classes. MSW increased in Hubei, China, by 30%, while in New York, USA, MSW increased by only 3.3%, and organic waste increased by 13.3% [8]. Mostafa et al. [8] attribute this to people's tendency to overeat when they stay at home. However, other cities in the US reportedly experienced a decrease in organic waste, as elaborated on below. Also, some classes produce higher amounts of certain types of waste. In developing countries, higher amounts of organic and food waste are produced, while in more developed, higher-income communities, more plastic, metal and glass waste are produced [7]. The same observation about the heterogeneity of changes in the composition and quantities of MSW has been produced by different countries. In Spain, food waste increased by 12% in 2020; however, in Italy and the US, food waste decreased due to infection considerations and a tendency to depend on home food [9,10].

This paper summarises, analyses, and critiques the experiences of different countries in dealing with the solid waste generated during the COVID-19 pandemic involving MW and MSW. The primary objective of this paper is to act as a reference for practitioners, policymakers, and decision-makers in developing and improving their SWM strategies based on the practical experience of other countries. The following sections investigate: (1) the methodology used in collecting the different studies included in this paper; (2) the impacts of COVID-19 on SW generation and the SWM sector in different countries, as well as the measures taken and guidelines issued by the government and different agencies to combat the disease transmission and maintain the service; and (3) several conclusions from the countries' experiences, and subsequently, recommendations for efficient SWM during the pandemic.

2. Research Methodology

Considering the rapid increase in the generation of the SWM and the issues accompanying its handling and management, this paper aims to explore the SWM experiences through (1) studying the impacts of COVID-19 on SW generation in seven countries presented as different case studies; (2) discussing the challenges faced by the SWM sector; and (3) exploring the different measures and guidelines for managing COVID-19's generated waste in general and the lessons learned. Examples of the impacts, challenges, and measures that will be examined in this paper can be found in Figure 1.

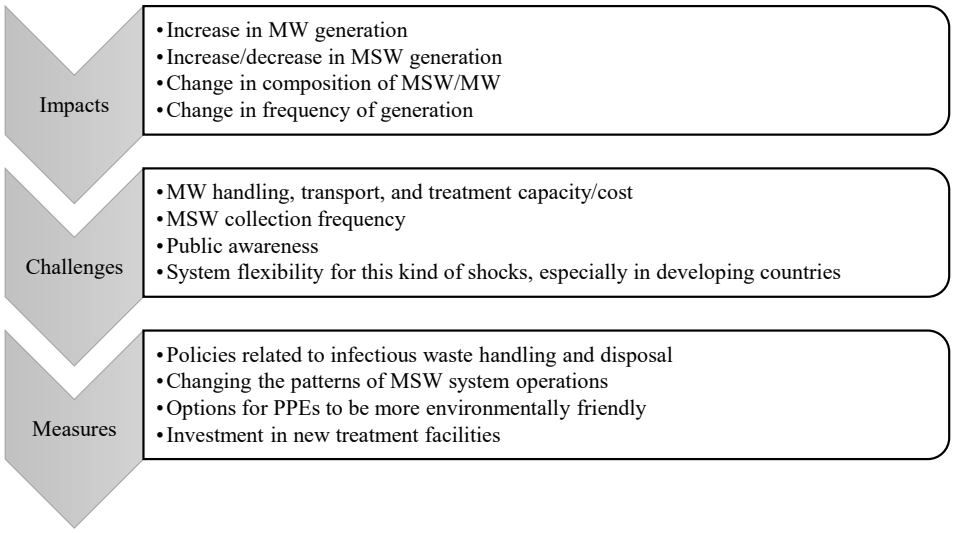

Figure 1. A summary of the impacts, challenges, and measures presented in this paper. Source: developed by the authors.

Figure 1 encapsulates a structured synthesis of the critical aspects examined in the manuscript regarding the impact of the COVID-19 pandemic on MW and MSW management. The impacts column highlights the significant shifts in waste generation patterns, such as increased MW due to the pandemic and variable changes in MSW generation due to altered consumer behaviours and lockdown measures. The composition of waste has also shifted, with more MW and hazardous waste (HW) and less commercial waste, as many businesses were closed. Additionally, waste generation frequency changed, likely due to the intermittent and unpredictable nature of lockdowns and the opening/closing of commercial activities. Challenges are identified as being multi-fold, focusing on the increased burden of handling, transporting, and treating the heightened levels of MW. Costs associated with these activities have also risen, putting additional strain on waste management infrastructure. The collection frequency of MSW has been challenged, as has adapting to the new waste generation schedules and ensuring the safety of waste management workers. Public awareness has become a critical issue, emphasising the need for proper waste segregation and disposal, especially of infectious waste. A significant challenge noted is the flexibility and robustness of waste management systems, particularly in developing countries, to withstand such unforeseen shocks. The measures column proposes strategic responses to the challenges posed by the pandemic. There is an emphasis on policy development focused on the handling and disposing of infectious waste to prevent further virus spread. Changes in MSW system operations are necessary to adapt to the new normal of waste generation patterns. Innovative approaches are encouraged to make personal protective equipment (PPE) more environmentally friendly, addressing the spike in PPE waste generation. Lastly, the figure suggests investments in new treatment facilities to cope with the increased and changing waste loads, ensuring environmental and public health safety. This figure provides a comprehensive overview of the intricate dynamics in waste management during the pandemic, underscoring the need for adaptive strategies and resilient systems to mitigate current and future challenges.

Based on the comprehensive analysis, it is evident that policy and technical measures and management recommendations can be formulated to address the ongoing challenges. These recommendations, however, are contingent upon several critical factors. Primarily, the extent to which the COVID-19 virus spread significantly influences the implementation strategies [11]. Additionally, the socio-economic dimensions of the country in question and the operational capacities of its Solid Waste Management (SWM) systems play pivotal roles in determining the efficacy of any proposed measures [12]. To ensure a holistic understanding and to encompass a wide array of potential scenarios, the case studies

selected were meticulously chosen based on the diversity of conditions under which SW was managed during the pandemic. Specifically, the countries selected for these case studies—the United States of America, India, France, and Brazil—were identified based on their high number of COVID-19 cases within their respective continents. This criterion facilitated a comprehensive analysis across geographical and socio-economic contexts [13].

Furthermore, South Africa and Australia were initially considered due to their significant case numbers in Africa and Australia, respectively. However, their exclusion was ultimately decided upon due to the comparatively lower infection rates and the scarcity of literature about their SWM conditions during the pandemic. In addition to the countries mentioned above, China and Italy were also incorporated as case studies. This decision was influenced by the initial impact of the virus on these nations and their subsequent experiences in managing and controlling the outbreak. Including these countries thus enriches the study by providing insights into the response strategies during the early stages of the pandemic [14]. Finally, Bahrain was considered to shed light on how a smaller country under constrained conditions was able to manage the crisis given the large percentage of infected cases to the total population (~40%) [15].

The seven case studies offer a diverse perspective, covering different continents, COVID-19 transmission curves, and developmental stages. This breadth of analysis is crucial for understanding the multifaceted challenges of SWM during the pandemic and for developing adaptable, practical strategies to mitigate these issues. An overview of the number of COVID-19 cases in the selected case studies is highlighted in Table 1.

Table 1. Number of COVID-19 cases in the selected case study countries at the beginning of 2024 [15].

	Severe Outspread		**The Country with the Highest Number of Cases in Each Continent**		**Smaller, Controlled Country**
Developing	-		Brazil 38,452,504	India 45,030,034	Bahrain 729,549
Developed	Italy 26,718,411	China 503,302 *	France 40,138,560	USA 111,557,170	

* China stops counting cases [16].

The relatively small numbers for China in Table 1 can be supported by the country's early, comprehensive response to COVID-19. China's strategies included strict lockdowns, widespread testing, contact tracing, and quarantine measures, implemented swiftly following the outbreak's identification. These efforts are well-documented in the literature and have been analysed for their effectiveness in controlling the virus's spread [17,18].

This paper considers that the first step in developing a sustainable SWM strategy during the pandemic is to identify the quantity of SW expected to be generated during this period. For this reason, theoretical models were used to estimate two leading indicators of SW associated with COVID-19: total daily face mask use and daily MW generation. The models are presented in Equations (1) and (2), adapted from the study conducted by [3], and the calculated quantities were then compared with the data available in the literature.

$$\text{Total daily facemasks} = \text{population} \times \text{urban population (\%)} \times \text{facemask acceptance rate (\%)} \times \text{average daily facemasks per capita}/10{,}000 \quad (1)$$

$$\text{MW (tonnes/day)} = \text{MW generation rate (3.95 kg/bed/day)} \times \text{number of COVID-19 cases (infected persons)} \quad (2)$$

3. Case Studies

3.1. Case Study 1: USA

3.1.1. Impacts and Challenges

As the country with the highest number of cases worldwide, it is imperative to discuss the USA's scenario. The country was expected to produce 8050 tonnes of MW daily during

each day of the epidemic, according to Haque et al. [19], while Culter [20] estimated that 2.5 million tonnes/month of MW were generated during the pandemic. This is six times higher than the 5 million tonnes/year of MW generated before the pandemic. Applying Sangkham's equations [3], the US was anticipated to produce 136,639 tonnes/day and use around 220 million face masks/day. This estimate is, obviously, considerably higher than other estimates, which raises suspicions about the accuracy of the assumption that 3.95 kg of MW is produced per day. It was estimated that prior to the pandemic, the USA generated 4.51 kg of MW/bed daily [21]. This waste is regulated by the states rather than the US Environmental Protection Agency (EPA) since the expiration of the MW Tracking Act with US federal agencies, including the US Occupational Safety and Health Administration (OSHA) and the US Drug Enforcement Agency (DEA), still involved in some aspects of the waste management process. Currently, MW is managed by the generating facility. It is mainly incinerated or treated onsite (i.e., steam sterilisation, thermal treatment, etc.) prior to landfill disposal [22]. The increase in MW has put tremendous pressure on the existing waste management systems and exceeded their capacities in many cases [23].

As for MSW, it was estimated that it experienced an increase of 20% in late April 2020 [24]. The composition of the waste also experienced a shift during this period. Some studies estimate that the waste contained a significant percentage of food waste, given the closure of restaurants and waves of panic buying [25]. Other studies estimate that the percentage of food waste in MSW decreased due to an increased trend of self-sufficiency and a tendency to cook at home [26]. MSW has also witnessed an increase in the amount of plastics, especially single-use plastic, which are perceived to be safer than recyclables to limit disease transmission [27,28].

Moreover, the World Health Organization (WHO) estimated that about 89 million medical masks were expected to be required to face the epidemic [29]. These masks usually end up with MSW and, in some cases, as litter [30]. Finally, the decrease in industrial activities due to lockdowns has decreased the amount of high-value recyclables from post-industrial activities [31]. MSW in the pandemic era is considered a source of infection given the virus' stability on different surfaces, which ranges from hours to days [32], and the fact that it contains fewer valuable recyclables, more single-use plastics and more organic waste [33].

COVID-19 has unexpectedly strained waste management sectors, including collection, recycling, landfilling, and incineration. Several cities in the USA have stopped their curbside pickup programs to better accommodate the increase in domestic waste generation [34]. Due to the lack of identification of recycling as an essential service in some cities, as mentioned by the Bureau of International Recycling [35], recycling is considered one of the most impacted sectors where several cities have limited or altogether banned their recycling programs to limit the disease transmission [30]. In California and Michigan, where recycling programs were allowed to continue, the number of incoming recyclables has significantly decreased. It is also reported that the Oregon Beverage Recycling Cooperative has received 45% less recyclables than the previous year [36]. The industry also lacks demand due to health concerns associated with recycled materials [27] and a drop in fossil fuel prices [23].

3.1.2. Management Measures and Guidelines

All of the changes have caused a paradigm shift in waste management in the USA. In order to cope with the changes and guide the industry sustainably and efficiently, several American authorities have issued statements and guidelines on the handling, transportation, and disposal of SW, both MW and MSW, during the COVID-19 pandemic [37]. The authorities include the Solid Waste Association of North America (SWANA), the Center for Disease Control and Prevention (CDC), the US OSHA and the US EPA. SWANA [24] has responded to the pandemic by emphasising that SWM is a crucial public service and should be maintained throughout the pandemic. The US OSHA issued guidelines for the safety of the MSW management personnel, stating that potentially infectious waste does

not require special precautions beyond those already instituted in the industry [38]. The CDC stated that COVID-19 waste is considered the same as any other MW and does not require special treatment [39]; however, they have issued guidelines for waste collectors and recyclers [40]. The US EPA [41] has released guidelines for recycling and sustainable food waste management during the COVID-19 pandemic covering households, institutions and businesses. Finally, the Association of State and Territorial SWM Officials [42] has compiled a list of national, state, organisational, and industry guidelines concerning COVID-19 and its solid waste handling.

3.2. Case Study 2: India

3.2.1. Impacts and Challenges

Yousefi et al. [43] reported that India's MW generation increased 82% during the COVID-19 pandemic. Sangkham [3] estimated that the MW reached more than 6490 tonnes/day, with about 381.2 million face masks used to fight disease transmission. Hantoko et al. [37] estimate that more than 26,450 tonnes of MW are generated daily, and 777 million masks are used with 2331 tonnes/day of discarded masks. Another estimate for MW generation in India is about 2160 tonnes/day by Haque et al. [19]. Additionally, a report by Krishnakumar [44] estimates that India generated more than 180 tonnes/day of MW, with a single area (i.e., Maharashtra) generating around 17% of the total MW. It was estimated that India generated more than 33,000 tonnes of waste, with a daily 146 tonnes of MW related to COVID-19 and COVID-19 patients (COVID-19 MW) [45]. Finally, it was estimated that 608 tonnes/day of MW were generated in India, with 10% to 25% hazardous waste and 90% to 75% non-hazardous waste [46].

While the equation assumes that 3.95 kg of waste per bed is produced daily, Ramteke and Sahu [47] claim that 500 g/day of MW per bed was generated before the pandemic, while the amount has currently reached 2.5 to 4 kg per bed. It is stated that Delhi alone generates 27 tonnes of non-COVID MW and 11 tonnes of COVID MW [48], while the Brihanmumbai Municipal Corporation (BMW) estimates that Mumbai generated 6 tonnes of non-COVID MW and 9 tonnes of COVID MW [47]. The significance of these data lies in their stark illustration of the pandemic's impact on MW generation, revealing a substantial increase that poses new challenges for waste management infrastructure and environmental health protocols.

Countrywide, a 55% increase in online shopping was noted [49]. Online shopping is generally associated with an increase in plastic waste. Given the concurrence of the national lockdown in India with the peak harvesting time, enormous amounts of food waste were generated [50]. Kamal [51] reported that the lockdown struck fear in farmers in Punjab about the fate of their perishable products, demanding an extension in the curfew to sell their products. Jadhav [52] adds that the transport system was disrupted, leading to the dumping of large amounts of vegetables and fruit supplies. The disruption in the transport system hindered farmers from transporting their food until it rotted [53].

In India, MW treatment facilities are not evenly distributed around the country. Some areas do not even have MW treatment and disposal facilities. Improper face mask handling has been observed in India, where the masks end up in landfills or open dumps [54]. Other kinds of solid waste end up in poorly managed open landfills [55]. B.I.R. [35] reports that the pandemic disrupted the recycling industry in India [35]. An additional problem with recycling is the inclusion of the informal/unorganised sector, which faces enormous challenges given the closed borders and lack of proper protective measures [33]. Finally, Kulkarni and Anantharama [9] estimated that more than 80% Indian urban waste is disposed of in landfills.

3.2.2. Management Measures and Guidelines

To face the food supply chain disruptions, the Indian government introduced measures for proper food supply to remote areas, effective food spoilage prevention, and timely transfer to markets to decrease food waste [45]. Sangkham [3] reported a lack of

standardisation of appropriate plastic waste collection methodology. UNEP and IGES [46] reported that 225 incinerators were installed to accommodate the increased generation of MW. Manuja [56] claims that 1.5 to 4.0 million people associated with SWM are expected to experience a health crisis during the pandemic.

The Central Pollution Control Board (CPCB) issued Guidelines for handling, treatment, and disposal of waste generated during treatment/diagnosis/quarantine of COVID-19 patients [48], while individual state pollution control boards provide more detailed guidance for specific stakeholders in their areas. The CPCB Guidelines recommend strict adherence to the existing 2016 Bio-MW Management Rules in addition to some new rules, including that COVID-19 waste be treated carefully through sealing in double-layered yellow bags to ensure that the bags would not be torn and avoid leakages, labelling to ensure priority treatment and disposal, separate sorting, and storing the waste before handing over to the staff. Quarantine facilities should communicate with Common Bio-MW Treatment Facilities (CBWTF) to coordinate their waste's timely collection and disposal. Deep burial shall be permitted only in rural and remote areas lacking access to CBTWF facilities. Hazardous waste incinerators may be used with special arrangements to dispose of COVID-19 waste exceeding the capacity of CBWTF and MW incinerators.

Moreover, the guidelines recommend that waste management personnel be equipped with personal protective equipment (PPE) and that COVID-19 waste collection vehicles be labelled. COVID-19 waste containers should be disinfected with 1% sodium hypochlorite daily. Finally, waste from quarantine camps and homecare facilities should be collected in dedicated bins and trolleys labelled "COVID-19" waste. Each state is responsible for assigning staff to manage MW and general waste, providing adequate PPEs, and ensuring regular sanitisation.

Also, it is worth noting that the guidelines recommend disposing of general waste from healthcare facilities and households with positive cases as per the local method of disposal of general waste. It is recommended that used face masks be torn to prevent reuse and kept in a paper bag for three days before disposal as general waste. Non-quarantined homes are recommended to disinfect their used face masks with ordinary bleach (5%) or 1% sodium hypochlorite before storing them in a closed bin for some time and then disposing of them to be treated as domestic hazardous waste and incinerated [57]. As for MSW management, little guidance has been provided by the Indian Government, according to Kulkarni & Anantharama [9]. It is reported that technological interventions and food inspectors were engaged to ensure the distribution of food products to restaurants and groceries to limit food waste.

3.3. Case Study 3: Brazil

3.3.1. Impacts and Challenges

In Brazil, the MW increase during COVID-19 compared to the pre-pandemic situation was not captured precisely, and the Sangkham equation will not be used again for estimation as it proved inconvenient for estimating MW generation and face mask count. This may be because 3.95 kg/bed/day is an overestimate of the MW generation in a developing country like Brazil. However, MW rates before COVID-19 did not exceed 700 tonnes/daily in the latest records before COVID-19. Assuming 0.5 kg/bed/day is the MW generation rate in Brazil, the total MW generation rate would be around 9400 kg/day, around ten times the value before COVID-19. Although this can be an acceptable estimate, it is still catastrophic for Brazil's treatment capacity, which will be overridden if the MW rate increases only twofold compared to normal conditions [58].

As for face masks, Nzediegwu and Chang [59] estimated that Brazil would generate around 150 million wasted face masks daily, with a total mass of 449 tonnes. On the other hand, MSW generation rates showed different trends. For example, street waste decreased in Sao Paolo compared to previous years due to lockdown conditions. However, household waste increased during some months of the lockdown and decreased during other months,

with an overall stable generation rate over the past ten years, including the pandemic year 2020.

3.3.2. Management Measures and Guidelines

The Brazilian Association for Environmental and Sanitary Engineering (ABES) and other concerned government and international organisations provided many recommendations on handling waste related to COVID-19 [60]. First, stop recycling activities because most recycling facilities in Brazil depend on manual sorting, which would spread the infection among workers, and this has already been applied by 14 cities out of 30 cities in Brazil. Moreover, SW generated by suspected or infected individuals should be dealt with as infectious waste (Category A1), and infected personnel should be isolated from the work environment. It was decided that new work protocols should be developed to save workers in the waste sector.

As a developing continent, Latin America already faces many challenges in adopting sustainable SWM practices, and now they must face the pandemic and effectively manage their waste to control infection spread. Therefore, the Brazilian government adopted some management practices to handle this crisis [61]. The measures stated, for example, that household waste should be double-bagged before disposal, landfill covering should be increased, and working conditions for waste workers should be improved, which included measures such as preparing and training more workers to cover the absentees during the pandemic waves and adjusting the shifts of waste collectors to the new disposal rates and times. The Brazilian government also intended to develop a contingency plan for any unexpected shocks in MSW generation rates.

3.4. Case Study 4: France

3.4.1. Impacts and Challenges

In France, MW treatment has increased between 40% and 50% during the pandemic [62]. This estimate has also been confirmed by Wei and Manyu [63]. The Sausheim plant in Grand Est has experienced an increase of 40%, while the Valo'marne plant in Ile-de-France has experienced a 50% increase [64]. Using Sangkham's equation [3], assuming that 3.95 kg/bed of waste is generated daily, France is anticipated to produce 23,437 tonnes/day. It was estimated that France generated 2.51 kg of waste/bed daily before the pandemic [21], but how much was generated during the pandemic is unknown. Thus, it cannot be confirmed whether the value obtained from the Sangkham equation is accurate or not.

On the other hand, the equation for calculating face mask usage, stated by Sangkham [3], estimates that 43 million face masks are used daily in France. This estimate is similar to the weekly 40 million surgical masks used in France [65]. This amount was influenced by the national and local regulations mandating the use of disposable masks in public places, according to Prata et al. [66] and Brooks et al. [67]. Almost no data about MSW generated in France during the COVID-19 pandemic are available.

France recognises the recycling sector as an essential service provider. Accordingly, the recycling centres remained open in France, like most European countries, during the pandemic despite the low activity and lack of demand for recyclables [35]. However, the waste management process in the country has been reported to be restricted during the pandemic [68]. It is reported that MSWM still follows regular SWM rules while trying to maintain proper waste sorting. The Amiens Métropole, Grand Besançon Métropole, Nantes Métropole, and Paris faced some interruptions of bulky waste collection and selective collection for commercial waste in specific areas, closure of collective composting units, and cancellation of reusable diaper renting systems [69]. However, up to 78% of French people maintained their sorting habits during lockdowns, and up to 18% improved their habits by paying more attention to their waste. It is also reported that 63% of the French people wanted to limit their waste generation [70].

3.4.2. Management Measures and Guidelines

A note on determining the conditions upon which MSW collection personnel may continue their service without exposure to COVID-19 was released by AMORCE [71], the French Network for information, sharing of experiences and support for local authorities in the field of energy transition, territorial waste management and water cycle management. It is reported that all recycling centres closed in March 2020, so when they reopened, they faced problems due to the waste volume and the personnel's safety conditions. The French High Council for Public Health published guidance on protecting waste collection personnel [72]. Some areas were advised to dispose of COVID-19 waste with normal MSW with double packaging or MW management techniques. Collection personnel were advised to follow proper hygiene measures and maintain the usual protection measures, such as PPE [72]. It is reported that France issued some national recommendations, including guidance on the protection of waste collection staff and especially MW, a statement on household and MW handling being regarded as essential services and an exception for unauthorised waste to be incinerated and landfilled while lifting all penalties on these services [73].

3.5. Case Study 5: China

3.5.1. Impacts and Challenges

Like every other part of the world where COVID-19 has spread, China has witnessed a massive spike in MW generation and is expected to witness that at every wave. The State Council of China found that COVID-19 resulted in around 470 tonnes of MW daily [3], and MW increased to around 11 kg/bed in China during the pandemic. This might be attributed to the need to deal with all the waste handled by human beings because it can transfer the virus. Looking at the results from the equations previously mentioned by Sangkham [3], it is estimated that MW associated with COVID-19 is about 365 tonnes daily, which is close to the previously mentioned amount, but the model used 3.95 kg/bed as an MW generation rate, and this is less than half the recorded number. The number of face masks predicted by the equations is around 500 million masks daily, with a total mass of 1485 tonnes.

Due to this chaotic situation, many challenges needed to be addressed on the MW management system [74]:

- The amount of waste generated overwhelmed the existing MW treatment facilities' capacity. For example, in Wuhan, the capacity of treatment facilities was 49 tonnes/day, while during the first COVID-19 wave, the city generated around 240 tonnes/day [75].
- Separation of infectious waste like face masks and other PPEs.
- Healthcare workers' compliance with WM guidelines.
- Safe and fast transport and disposal of MW.

Unlike MW, MSW is expected to decrease during the times of the pandemic waves. The State Council in China reported that while the MW generation was increased by more than 370%, the generation of MSW showed a 30 decrease after the outbreak of COVID-19. These results agree with the findings of Klemeš et al. [23].

3.5.2. Management Measures and Guidelines

National and local governments in China have undertaken many measures to deal with the waste associated with COVID-19. The Ministry of Ecology and Environment of the People's Republic of China issued a notification on the environmental management of MW during the pandemic and technical guidelines on MW disposal. More policies and regulations were introduced by local governments [76]. For example, priority should be given to pandemic-related MW. It also followed other countries' steps in separating disposed waste and direct transport of the MW and possibly infectious waste. MW shall be incinerated on site or disposed of in environmentally safe places for areas that cannot do centralised waste collection, such as rural areas. In Shanghai, the city suspended separate

waste collection to decrease the contamination risk caused by separate waste handling and transport.

Several changes were made to the management strategies and practices on the country's national and local levels [77]. They set up special garbage collection containers in hospitals or places where suspected coronavirus patients exist to ensure separate handling of infectious waste. In Suzhou, one of the leading cities in waste management, 11,000 separate bins for face mask disposal were installed. In Hubei, the hardest-hit Chinese province, the capacity to dispose of MW doubled in less than three weeks from 180 t/d to 373 t/d. Also, MW treatment capacity in China jumped to 6000 t/d from 4900 t/d in the 'pre-coronavirus' times, and working hours were changed for sanitation staff to handle the increase in waste generation.

3.6. Case Study 6: Bahrain

3.6.1. Impacts and Challenges

Like other countries, the COVID-19 pandemic has caused a significant increase in the generation of MW, almost double the amount of MW the country generated prior to the pandemic [78]. Experts noted a substantial increase in MW, predominantly from COVID-19 treatment facilities and regular healthcare establishments. The Awali MW incinerator in Bahrain reported an increase of almost 50% in MW received for treatment at the facility [79].

Al-Omran et al. [80] have estimated the amounts of COVID-19 MW generated for Bahrain during 2020 and 2021 and found that around 35.5 kg/day of face masks, 1864 kg/day of PPE for health facilities, and 13,000 kg/day is generated. This study utilised Sangkham [3] equations with a face mask acceptance rate of 80% and an average of 1 daily mask per capita.

The generation of MSW, particularly from the food sector, has increased due to rising demand for home delivery services during lockdown. Restaurants' use of single-use packaging and utensils has further increased the amount of plastic waste in MSW. Bahrain International Airport provided detailed data, albeit not fully representative of broader economic trends. In 2020, general waste decreased by 45% compared to 2019.

3.6.2. Management Measures and Guidelines

The Government of Bahrain established the National Medical Task Force for Combating the Coronavirus (COVID-19). This team was responsible for devising the country's approach to limiting disease transmission, including introducing lockdowns, limiting gatherings, and face masks and PPE mandates. The efforts of the Task Force were showcased in the country's management of disease transmission. According to the WHO 2020 Situation Report, Bahrain was among the world's first countries to have administered COVID-19 tests to 50% of its population [81]. In 2021, the WHO reported that Bahrain was ranked first (out of 122 countries) in November's Nikkei COVID-19 Recovery Index. With that, significant amounts of MW and infected MSW are generated.

Before the pandemic, Bahrain relied on public waste segregation initiatives organised by environmentally conscious groups. Unfortunately, these initiatives were largely unsuccessful and were suspended. During the pandemic, these initiatives were further impeded by the prohibition of gathering and lockdown regulations and the public's preoccupation with potential health risks [79]. Thus, in Bahrain, waste originating from healthcare facilities was treated as MW and incinerated, while waste generated elsewhere (whether infected or not) was treated as general waste and landfilled [79].

In December 2020, the Ministry of Health issued regulations for managing hazardous waste for healthcare. These regulations complement Legislative Decree No. 10 of 2019, which established requirements for general hygiene, including MW management. These include regulations on MW transportation through licensed companies and proper disposal requirements [82].

3.7. Case Study 7: Italy

3.7.1. Impacts and Challenges

In Italy, the spread of COVID-19 was accompanied by an increase in using face masks and PPEs and an increase in hospitalised cases, which has led to a substantial increase in MW generated [83]. Using the equations stated by Sangkham [3], the total number of face masks used daily in Italy is expected to reach 33.4 million masks during the pandemic waves, and the total mass of face masks disposed daily should reach 100 tonnes which is around 0.12% of the total MSW produced in Italy [84], a small proportion of the total waste produced, even after the decrease of the total MSW by 27%, the proportion of masks would reach 0.16%. The total mass of MW is estimated to be around 17,000 tonnes daily.

Looking at the MSW generation, we find a decreasing trend during the outbreak. This can be attributed to the strict lockdown measures the Italian government took, which left many Italian cities almost empty for several months. It was predicted that MSW in Italy would decrease by 20 tonnes in 2020 [85], and this decreasing trend was observed already during 2020. In Trento, MSW generation in March 2020 was 18.5% lower than the March average for the past ten years. This trend was also recorded in Milan, where MSW decreased by 27% between March 2019 and March 2020 [86].

However, all of this can be misleading because it only considers the situation during extreme lockdown, which can change when easing the conditions of social distancing. If a closer look is taken at food waste, it was found that COVID-19 changed food consumption patterns significantly due to the stoppage of all commercial activities due to lockdown conditions. This caused a change in the proportion of the waste components. For example, packaging waste increased due to dependence on food delivery. Food waste generation decreased, although food consumption increased during the pandemic due to different factors, including fear of not finding food. Italy recorded one of the lowest food waste values of 0.13 kg/day/person compared to other European countries, like Germany, Croatia and Finland, which recorded 0.14, 0.21 and 0.41 kg/day/person, respectively [87].

3.7.2. Management Measures and Guidelines

Although Italy seems so overwhelmed by the pandemic that they did not focus very much on waste management in terms of policy actions and shifting management practices, Italy still has taken some measures recommended by the European Union or initiated by the Italian government. These practices cover the gap in COVID-related MW management, prioritise COVID-related waste in treatment and disposal over other waste, and monitor any changes in waste flows [88].

The government of Italy has adopted many measures related to the collection, treatment, and disposal of MSW and MW [30]. The government has prohibited infected people from sorting their waste. The government also stopped recycling activities. Contaminated MSW should be incinerated either in thermo-chemical treatment plants or mechanical–biological plants. The European Union has also provided general guidelines for handling MSW and MW [89]. Member countries should plan the capacities of treatment facilities and storage facilities when needed, and when using exceptional processes, the difference between these processes and regular ones should be determined. Waste from cleaning healthcare facilities should be treated as infectious waste.

Italy issued guidance on managing MSW from affected households, and the EU recommended more management guidelines [83,89]. Some supermarkets provided polypropylene light gloves instead of nitrile/latex gloves to facilitate dispersion away from supermarket entrances. Moreover, PPE bins have been used outside every supermarket to prevent dispersion. Moreover, the European Commission has started the Coronavirus Response Investment Initiative, which will help provide member countries with cohesion policy funds that will consider SWM.

4. Results and Discussion

The countries' experiences offered a broad spectrum of potential measures to combat the added pressure of the new COVID-19 usage waste streams. All countries have faced an increase in face masks usage in the hundreds of millions, corresponding to thousands of tonnes. An increase in face mask usage, their disposal as MSW, lockdowns, and changes in activities, such as an increase in online shopping and food hoarding, have all led to an increase in MSW ranging from 20% to 40% and a change to its composition. In the case studies, MSW was characterised by increased single-use plastics, food/organic content (in some cases), and decreased recyclables and high-value waste during the pandemic. Estimations for the generated MSW were unavailable for all countries, which is a research limitation. The first step to properly manage SW is to estimate the amount to collect, treat, and dispose of it.

The model developed by Sangkham [3] to predict the amount of MW and face masks produced daily is an exciting attempt to provide a meaningful estimate of fundamental indicators (i.e., total face masks used daily and total MW produced daily) in SWM in such a pandemic, especially with the difficulties of collecting accurate data about these indicators. However, these equations have some limitations which can be addressed. First, the equation for calculating the number of face masks assumes that the mask acceptance rate is constant and arbitrarily chosen. However, this number cannot be constant because different societies react to using face masks differently, and this number can be correlated to other variables like the total number of cases of COVID-19 in the country. Second, the equation used to calculate MW assumed a constant rate of MW generation of 3.95 kg/bed, although this number is different between different countries, and this difference is seen most between developed and developing countries.

These limitations caused the results from the equations to diverge significantly; sometimes, they provide unacceptably different results from recorded data, such as in the case of Brazil, where the model predicted MW to be 74,140 tonnes/daily during COVID-19, although the number was about 700 tonnes before the pandemic. However, when we used 0.5 kg/bed/day as the rate of MW generation, the results returned to the acceptable range but were still ten times the value before COVID-19, which is very different from the reported world average of a 40% increase in MW.

The increase in waste generation due to the pandemic has threatened SWM strategies globally. Generated waste from COVID-19 confirmed or suspected cases is treated as MW in most countries, which has added pressure to the existing treatment facilities. General waste from non-COVID-19 households is treated as general waste in most case studies, such as India and the US, despite this waste having the potential for disease transmission, given that an asymptomatic patient can reside in the household. The increase in MW generation has, in many cases, exceeded the existing capacity of MW treatment centres/incinerators, which has led some countries, such as India, to expand their treatment/incineration capacities or look for alternative treatment methods (e.g., incineration) with common hazardous waste. Moreover, improper disposal of potentially infected MSW endangered informal waste collectors around the globe, especially in developing countries, where they are unofficially included in the national SWM strategy. Waste recycling is one of the hardest hits to SWM sectors due to the COVID-19 pandemic since several countries have entirely suspended their recycling activities because of (1) the fear of disease transmission due to recycling or (2) the response to the lack of demand for recycled products. The main disposal techniques during the pandemic include incineration and landfilling. The selected case studies have followed several strategies to combat the spread of the disease, which can be summarised in Table 2.

Table 2. Summary of the measures taken by each of the selected case studies.

Aspect	USA	India	Brazil	France	China	Italy	Bahrain
General COVID-19 Waste Guidelines	US OSHA and the CDC treat COVID-19 MW as normal MW. Each state issued its guidelines regarding SWM during COVID-19.	Government Guidelines for the handling, managing, and disposing of COVID-19 waste from quarantine centres and homecare facilities.	ABES recommendations on COVID-19-related waste handling. COVID-19 MW was treated as normal MW.	Disposal of COVID-19 waste with normal MSW with double packaging or MW management techniques.	The Ministry of Ecology and Environment of China guidelines on pandemic-related MW management emphasise separation and prioritisation of COVID-19 waste over others.	The EU guidelines on the handling of MSW and MW. The Government of Italy also issued guidelines on MSW handling from affected households.	Waste originating from healthcare facilities was treated as MW and incinerated, while waste generated elsewhere (whether infected or not) was treated as general waste and landfilled
Food Waste Management	UNEP sustainable food waste management guidelines cover households, institutions, and businesses.	Measures have been proposed to decrease food waste, such as using food inspectors and technological interventions to ensure food delivery.	N/A	N/A	N/A	N/A	N/A
Waste Collection	N/A	Separate, labelled bins are available for COVID-19 waste.	N/A	N/A	Additional bins were installed to collect PPE and face masks.	Additional bins for PPE and face masks.	N/A
Waste Management Personnel	US OSHA and the CDC guidelines for waste personnel protection.	The CPCB guidelines for protecting waste personnel.	New protocols for waste workers, including modifying schedules and staffing.	The HCSP guidelines for waste personnel protection.	Adjusted schedules and staffing to minimise disease transmission.	Adjusted schedules and staffing.	N/A
Waste Recycling	Waste recycling is suspended in some states and continues to have limited capacity in others.	N/A	Recycling is suspended in many cities	Recycling suspended	N/A	Recycling suspended	N/A
Waste Incineration	N/A	225 new incinerators installed.	N/A	Incineration of unregulated waste without penalties	Capacities have increased for disposing and treating MW.	N/A	Waste incineration increased by 50%
Waste Disposal	N/A	N/A	Landfilling activities increased.	N/A	N/A	N/A	N/A

N/A: Not available.

From Table 2, most countries are concerned about the health of their waste collection personnel and have issued guidelines on how to deal with the waste. However, in the cases of the USA and India, these guidelines merely advise the personnel to follow their standard protection measures. For a developed country like the USA, this statement poses no problems, but for India, where rag pickers and the informal sector are involved in SWM, this statement could put the waste collection personnel at risk. The proper separation of potentially infectious waste from general MSW is imperative to ensure the safety of the collection personnel and the effectiveness of the SWM industry. Moreover,

recycling was suspended in many countries, which has placed undue pressure on other treatment/disposal techniques such as landfilling and incineration. Landfilling is the least favoured option, given its environmental impact and physical footprint, while incineration could be considered a viable option with proper pollution abatement techniques. It is recommended that countries invest in expanding the capacities and efficiencies of their incineration system to ensure proper handling of potentially infectious waste in the future. Finally, during times of crisis, waste compositions change, and governments must employ proper monitoring techniques to ensure proper and timely treatment/disposal of the different waste streams within the existing capacity of the SWM system.

5. Conclusions and Recommendations

Concluding this comprehensive review on the implications of the COVID-19 pandemic on MSW and MW management worldwide, it is evident that the pandemic has profoundly affected waste management systems globally. The abrupt increase in MW due to the disposal of personal protective equipment and changes in MSW due to lockdowns and shifts in consumer behaviour have presented significant challenges. These challenges have necessitated immediate responses to prevent potential public health risks and environmental impacts.

Investigating case studies across various countries, including the USA, India, Brazil, France, Italy, and China, has revealed challenges and innovative responses to solid waste management during the pandemic. These responses have ranged from increased incineration capacity changes in waste collection protocols to the suspension of recycling programs in some cases to prevent virus transmission. Moreover, the pandemic has underscored the critical role of waste management workers, highlighting the need for adequate protective measures to safeguard their health.

Based on the analysed case studies, several recommendations can be made to enhance solid waste management during a pandemic. First, there is a need for the development and implementation of robust waste estimation models that can provide accurate predictions of waste generation rates during health crises. Such models are crucial for planning and ensuring that waste management systems are adequately prepared to handle increased loads, particularly MW.

Second, public health emergencies like the COVID-19 pandemic call for adaptive waste management policies that swiftly respond to changing waste generation patterns and compositions. This includes ensuring the protection of waste management personnel through adequate training, provision of personal protective equipment, and clear guidelines on handling potentially infectious waste.

Third, the pandemic has highlighted the importance of investing in waste management infrastructure, including expanding incineration capacity and adopting technologies to treat and dispose of MW safely. Enhancing the resilience of waste management systems to handle sudden increases in waste volumes is essential for mitigating potential public health and environmental risks.

Moreover, suspending recycling programs in some regions during the pandemic underscores the need for innovative solutions to maintain recycling efforts during public health crises. This may include the development of contactless collection methods, increased automation in sorting and processing, and public education campaigns to encourage safe recycling practices.

In addition to these findings, this study stresses the critical need for integrating these strategies into current waste management policies to enhance both effectiveness and efficiency. Governments and relevant authorities should consider revising waste management protocols and guidelines to incorporate flexible measures that can be swiftly implemented in times of a public health crisis. This includes legal and regulatory frameworks that allow for quick adaptation to changes in waste types and quantities.

Practically, this research suggests that municipalities and waste management entities could benefit from developing crisis response strategies that prioritise public health while

maintaining environmental protections. This could involve establishing partnerships with private sector technology providers to innovate more resilient waste processing and disposal solutions that can quickly adapt to increased demands, as observed during the pandemic. By learning from the experiences of different countries and implementing the recommended strategies, it is possible to ensure that solid waste management can effectively contribute to public health and environmental protection, even in the face of a global health crisis.

In conclusion, the COVID-19 pandemic has presented unprecedented challenges to solid waste management systems worldwide. However, it also offers an opportunity to reevaluate and strengthen these systems for future resilience. By learning from the experiences of different countries and implementing the recommended strategies, it is possible to ensure that solid waste management can effectively contribute to public health and environmental protection, even in the face of a global health crisis.

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