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COVID-19 and medical waste management: challenges and the urgency for systemic change

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Abstract. The COVID-19 pandemic has not only caused a global health crisis but has also posed significant challenges to medical waste management. The rapid increase in waste generation, including used personal protective equipment (PPE), presents a serious threat to the environment and public health. Improper waste management leads to the accumulation of nonbiodegradable plastics and increases the risk of secondary infections, particularly in developing countries where infrastructure is limited. Our review aimed to analyze the impact of the COVID-19 pandemic on the scale of medical waste generation, its management, and to assess the environmental and health consequences. During the COVID-19 pandemic, waste generation increased by 18-425%, intensifying pollution and associated health risks. Inadequate disposal practices, including incineration without advanced technologies, release toxic compounds, such as dioxins and heavy metals, adversely affecting air, water, and soil quality. Systemic changes, including improved waste segregation, recycling, and the adoption of environmentally friendly technologies, are necessary to minimize the negative impacts of the pandemic on both the environment and public health and to prevent similar crises in the future.

Key words: COVID-19, medical waste, personal protective equipment, environmental pollution

Introduction

Since December 2019, the world has been facing a previously unknown health challenge: the COVID-19 pandemic caused by the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2). SARS-CoV-2 belongs to the genus Betacoronavirus (Beta-CoV) and is a member of the Coronaviridae family. The fast-spreading COVID-19 pandemic has created a new problem for medical waste management (Xie et al., 2023; Liang et al., 2021).

As infection rates increased, so did hospital admissions, resulting in a surge in medical waste from single-use diagnostic tools and treatment materials used during patient care. The amount of personal protective equipment (PPE) by healthcare workers also increased for apparent reasons. In order to prevent infection, staff members were typically sent to the patient wearing disposable masks and frequently in disposable suits. Medical waste recycling systems were under a lot of strain as a result of the unexpected and abrupt crisis. Only in the hospital setting did the amount of PPE used increase with each additional gravely infected individual. The use of masks and gloves has also increased outside hospitals. In many nations, it became mandatory to restrict the number of patrons in businesses and to package items so that they did not come into contact with other consumers. Disposable gloves and bags are frequently used. Due to the divergence of data from different centers around the world, as well as difficulties in categorizing waste, there are challenges in analyzing the amount of waste generated in connection with COVID infection. Studies indicate that the pandemic led to a substantial rise in medical waste production, with local increases ranging from 18% to 425%, depending on the region and healthcare capacity (Xie et al., 2023; Liang et al., 2021). The amount of COVID-19-related garbage generated daily increased from 40 to 240 tons only in Wuhan, China, the site of the virus's initial detection (Behera, 2021). Prior to the pandemic, the United States was predicted to produce 5 million tons of garbage annually; during the pandemic, this increased to approximately 2.5 million tons per month (i.e. ~15 million tons annually). This enormous increase cannot remain without consequences. Currently up to 11 kg of hazardous waste per hospital bed per day (kg/bed/day) is produced in high-income countries, compared to up to 6 kg in low-income ones (Janik-Karpinska et al., 2023)

This narrative review analyzes worldwide data on the management of medical waste, explores the environmental and public health consequences of increased medical waste generation, and proposes actionable strategies for improving waste management practices.

This study aimed to analyze the impact of the COVID-19 pandemic on the scale and nature of medical waste generation. This study presents global statistics on medical waste management, examines the environmental and health implications of excessive medical waste production, and presents recommendations for waste management strategies.

Materials and methods

This study is a narrative review based on the analysis of available scientific literature and international reports concerning medical waste generation and management during the COVID-19 pandemic. The literature search was conducted using major scientific databases (e.g. PubMed, Scopus, and Web of Science) with the following keywords: “COVID-19”, “SARS-CoV-2”, “medical waste”, “healthcare waste”, “infectious waste”, “hospital waste”, “personal protective equipment”, and “waste management". Peer-reviewed original articles, review papers, and official reports published between 2005 and 2024 were considered, with priority given to studies published after 2020. Studies were excluded if they were not related to waste management or environmental impacts of COVID-19, lacked sufficient methodological detail, were duplicates, or were not available in full text. Global data were reviewed to assess changes in waste volume, disposal practices, and associated environmental and public health impacts.

Results

Impact of the COVID-19 pandemic on the fight against single-use plastics

Long before the pandemic, the detrimental effects of single-use plastics (SUPs) on the environment were widely recognized. This issue involves not only the long decomposition time of polymers, but also the difficulties in recycling and waste disposal. Due to growing concerns about the future of the planet, many initiatives have been proposed worldwide to prevent plastic from entering the environment and reduce its environmental footprint. Many countries have banned or restricted the use of SUP. Plastic bags, coffee cups, soda and water bottles are used only once before being thrown away, and their recycling rate is extremely low (approximately 12%) (Shams et al., 2021).

The COVID-19 pandemic completely reversed the global trend of reducing SUPs consumption. This has also led to a significant and rapid increase in global medical waste production, which typically consists of 85% general non-infectious waste (e.g., packaging and non-contaminated containers), 10% hazardous or infectious waste (e.g., sharps and soiled dressings), and 5% chemical or radioactive waste (e.g., pharmaceuticals and radioactive materials) (Haque et al., 2021). The World Bank has already warned that this pandemic will undo the years-long trend of limiting SUP sales. Since protecting lives was the greater good, SUP PPE for both healthcare professionals and regular people, including face masks, surgical masks, and face shields, started to be mass-produced. Most PPE is composed of polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS), materials that are seldom recycled. Furthermore, the pandemic lockdown has had a major effect on plastic recycling facilities worldwide, leading to the improper and unlawful discharge of plastic garbage into land and oceans (Shams et al., 2021; Joseph et al., 2021).

Meta-analyses from around the world have shown that the COVID-19 pandemic has led to a global increase in the use of SUP PPE. According to Statistics Canada, 3.88 million disposable gloves, 1.76 million masks, and 26.6 million disposable gowns were used between June and December 2020 in Canada alone (Shams et al., 2021; Statistics Canada. Health characteristics, annual estimates: Personal protective equipment demand and supply, 2022). As the demand for disposable masks (such as N95) grew, record numbers of masks were created. In 2021, 3M manufactured more than a billion of these masks. The US Department of Health and Human Services stated that the demand for face shields surged by more than 300%, whereas the demand for gloves reached 8.7 billion each month (Shams et al., 2021; Parashar and Hait, 2021). In August 2020, the UK National Health Service distributed over 10 million SUP PPE per day. During the COVID-19 pandemic, the use and production of disposable masks increased dramatically worldwide, including a 450% increase in mask production in China reaching 900 million masks daily, over 85 million masks used in Brazil in August 2020, and approximately 40 million disposable surgical masks used weekly in France (Shams M et al., 2021; Parashar and Hait, 2021; Silva et al., 2020; Khan et al., 2023). According to the source data, Japan recorded a remarkable increase in mask production, and by April 2020, the daily production reached 600 million (Shams et al., 2021; Parashar and Hait, 2021).

However, several variables, including proper waste classification, regulation of SUP import and export, and equipment disposal affect the accuracy of these numbers. An example of a local meta-analysis conducted in a densely populated Turkish city provides a realistic assessment of the rise in plastic medical waste. The monthly waste output increased from 79,027 kg to 116,714 kg. It was determined that 75% of the total trash was from public hospitals, making them the main producers. The rate of medical waste output per bed day grew significantly from 0.86 kg/bed day prior to the pandemic to 1.34 kg/bed day in 2021. Meta-analyses conducted in 2019-2020 reported an approximate 48% increase in medical waste during the COVID-19 pandemic compared to previous years. Importantly, these data include only waste collected in healthcare facilities and exclude PPE used in community, such as face masks (Silva et al., 2020). Based on global evidence, these results show that COVID-19 pandemic significantly increased waste generation beyond levels expected for the 2040s under normal conditions (Shams et al., 2021; Hanedar et al., 2022).

Excessive Generation of Medical Waste and Its Potential Environmental Consequences

During the COVID-19 pandemic, the heightened demand for medical items, combined with limited recycling and waste management infrastructure, resulted in widespread environmental and public health challenges. This included air and water pollution, higher risk of infections from improperly disposed materials, and the accumulation of non-biodegradable plastics, further stressing ecosystems (Haque et al., 2021). The pandemic has also resulted in increased medical waste being generated outside healthcare facilities, such as in homes where people are self-quarantining or sick. This has contributed to a rise in infectious waste (Yousefi et al., 2021).

Medical waste management became a significant challenge, as many households lacked proper disposal systems and clear guidelines for handling potentially infectious waste. Without adequate training or resources, people may improperly dispose of contaminated items, such as used masks and gloves, increasing the risk of exposure to harmful pathogens (Das et al., 2021). Source segregation is essential for ensuring safe handling and disposal (Haque et al., 2021). Its removal emits a mixture of greenhouse and toxic gases. These include carbon monoxide, sulfur dioxide, nitrogen oxides, fluoride, various metals (e.g., mercury, lead, cadmium, copper, and lead), dioxins, and other volatile organic compounds (Zakaria et al., 2005; Ye et al., 2022; Sharma et al. 2013). These pollutants primarily contaminate the atmosphere, but metals can also affect water and soil, leading to the pollution of water sources and potential food supplies. Metals can bioaccumulate in the environment, making them difficult to remove and posing a long-term risk to the food chain (Ye et al., 2022).

Heavy metals, including Pb, Cr, Cu, Cd, Ni, Mn, and Zn (Valavanidis et al., 2008), are not destroyed during incineration but are concentrated in the ash residue. Its improper incineration, especially in developing countries lacking advanced technologies, can generate toxic compounds, exacerbating waste management challenges (Sabiha-Javied et al., 2008; Kenny and Priyadarshini, 2021). Furthermore, heavy metals in ash residues become more soluble and bioavailable, while high-temperature incineration increases the risk of inhalation of vaporized metals, potentially contributing to inhalation-related diseases (Sabiha-Javied et al., 2008).

Different disposal methods are essential for handling various categories of medical waste. The two main types of disposal technologies for medical waste are incineration and non-incineration methods, each with specific applications and implications (Ye et al., 2022).

Incineration is a process by which infectious waste is burned, producing combustion gases, non-combustible residues, and ash. However, the World Health Organization (WHO) in its 2004 policy paper and the Stockholm Convention raised a dilemma about the risks associated with the incineration of medical waste, as it was found to cause health deterioration (Sharma et al. 2013). Medical waste incinerators release a wide variety of pollutants into the air, including compounds known as dioxins, which are significantly more hazardous than other gases (Ye et al., 2022). Dioxin intake has been associated with cancer development in individuals living close to incinerators. Moreover, it can lead to birth abnormalities, hormonal imbalances, a decline in the sex ratio, and respiratory symptoms. Incineration also leads to environmental degradation - soil acidification, dioxin and heavy metal contamination. This can lead to further contamination of agricultural products (Sharma et al. 2013). Foods of animal origin, particularly those high in fat, are primary sources of dioxin and polychlorinated biphenyls (PCBs) exposure due to their lipophilic properties. The highest levels of these compounds are found in eel meat and fish liver, followed by dairy products, raw milk, and hen eggs, due to their accumulation in fatty tissues. Plant-based foods typically have much lower contamination levels (European Food Safety Authority. Update of the monitoring of levels of dioxins and PCBs in food and feed, 2012). Animal-based foods account for approximately 90-95% of human dioxin intake. Moreover, animals with longer lifespans are more likely to accumulate dioxins in adipose tissue, thereby increasing human exposure through consumption (Vnunec et al., 2024). According to the European Food Safety Authority (EFSA), the tolerable weekly intake (TWI) for dioxins and dioxin-like PCBs was revised to 2 pg/kg body weight in 2018. This level is deemed protective against long-term adverse effects on the immune and reproductive systems and is not expected to negatively affect human development (EFSA Panel on Contaminants in the Food Chain (CONTAM), Knutsen HK, Alexander J, et al., 2018).

Developing countries in Asia, such as Cambodia, the Philippines, Thailand, India, Malaysia, Indonesia, Bangladesh, Vietnam, and Palestine, are widely perceived to dump municipal solid waste (MSW) in poorly managed and open landfills (Sangkham, 2020). During the COVID-19 pandemic, Iran imposed a ban on waste separation and recycling; however, illegal waste segregation persisted. An example of balancing infection prevention with the zero-waste concept was implemented in Italy, where only infected residents were prohibited from waste segregation. In Tehran, the pandemic led to a significant increase in landfilled waste, and infectious waste was managed through disposal in double or triple bags at the Aradkouh site.

Additionally, hospital waste production exceeded the WHO recommendations, with a notable rise in the volume of infectious waste generated during the pandemic (Zand and Heir, 2020).

In the least developed countries in Africa, there are no national guidelines for the proper medical waste management. In 90% of cases, incineration is used without advanced technologies in open fields. Regular disposal of pharmaceutical waste into 'general waste' has led to the entry of various medications into landfills and aquatic environments. This has affected the quality of the soil and water that residents and wildlife rely on, due to harmful residuals and emissions from incinerators (Zand and Heir, 2020).

Excessive Generation of Medical Waste and Its Potential Health Consequences

Pollution is the leading environmental cause of disease and premature death worldwide. Inefficient waste management practices, particularly landfilling, release highly toxic contaminants such as dioxins and furans, which are linked to severe health conditions, including cancer, liver failure, and respiratory diseases. Moreover, even at levels deemed tolerable, air pollution worsens morbidity related to respiratory and cardiovascular diseases and contributes to premature mortality. Public health experts widely agree on the urgency of addressing these issues. Beyond individual health consequences, increasing air pollution imposes significant social costs, amplifying the burden on communities and emphasizing the need for sustainable waste management solutions to mitigate these effects (Kenny and Priyadarshini, 2021).

Emissions from waste management processes, including greenhouse gases, smog, and air pollutants, significantly contribute to global warming, acid rain, and soil and water resource acidification (Ye et al., 2022). Key pollutants, such as carbon monoxide, carbon dioxide, nitrogen oxides, and sulfur dioxide, play a major role in exacerbating heat-related illnesses and mortality, especially in vulnerable populations, such as the elderly and those living in developing countries. Additionally, global warming has facilitated the emergence of parasitic diseases in previously unaffected regions, further straining global health systems (Kenny and Priyadarshini, 2021).

Role of surface contamination in the spread of SARS CoV-2 - advantage of SUPs

The use of SUP during the COVID-19 pandemic was prompted by research showing that the SARS-CoV-2 survival rate on different surfaces varied from hours to days, depending on the material type (Geng and Wang, 2023; Janik-Karpinska et al., 2023). Table [Table 1] presents the variable time of virus decay on different surfaces. The shortest virus survival time was observed on tissue paper, whereas the longest persistence was reported on the surface of the surgical mask. However, under favorable environmental conditions, viral viability could extend up to 28 days on certain materials. (Geng and Wang, 2023).

Table 1. Role of the surface in virus decay (Geng and Wang, 2023).

Type of material	**Time of virus decay**
Tissue paper	30 min - 3h
Wood	1 day
Cloth	1 day
Surgical mask	7 days
Paper Banknote	2 days
Glass	2 days
Stainless steel	4 days
Plastic	4 days

Several variables, including temperature, relative humidity, and strain on the surface, may affect the virus's ability to survive. According to one study, SARS-CoV-2 RNA can survive for 11–21 days in serum samples, 17–31 days in stool samples, and 13–29 days in respiratory samples (Behera, 2021). Therefore, disposing of single-use equipment was necessary, as contact with infected individuals resulted in contamination of the surroundings. Interestingly, according to current knowledge it has been shown that fomites may not be as critical to the transmission of SARS-CoV-2 as initially suspected (Janik-Karpinska et al., 2023). Studies on household surfaces, such as door handles, water taps, toilets, and kitchenware, have examined the presence of SARS-CoV-2 RNA. Kitchen surfaces had the highest rate of aggregation, whereas public corridor surfaces had the lowest percentage. It is important to note that the detected material does not necessarily translate to the infectious potential of the virus. In this context, its rapid decline over time and heterogeneous presence suggest a limited role of fomite transmission in real-world settings (Lin et al., 2024).

Risk of Secondary Infection Transmission Due to the Increased Volume of Medical Waste

There is an increased risk of secondary transmission due to improper storage, transport, and management of medical waste, especially in developing countries (Sangkham, 2020, Zand and Heir, 2020). Healthcare workers and nearby communities are primarily at risk as a result of potential needle-stick injuries, burns, and exposure to pathogenic microorganisms, even from discarded face masks (WHO, 2022; WHO, 2022; Hantoko et al., 2021).In many developing countries, solid waste, including PPE, is often disposed of in poorly managed landfills, where waste pickers, who lack proper protective gear, scavenge for recyclables. This exposes both humans and animals to potential viral contamination, contributing to the spread of diseases, such as COVID-19. Furthermore, reused contaminated plastic bottles, commonly used for packaging drinks in these regions, represent an additional risk factor for viral transmission (Ali and Parvin, 2022). There is also the risk of microplastic contamination, which further increases the potential for virus spread (Yousefi et al., 2021). The lack of clear waste management protocols in many regions exacerbates the spread of infectious diseases, posing a threat to public health and the environment (WHO, 2020).

Discussion

Recommendations and Strategies for Future Medical Waste Management

The WHO has played a key role in developing waste management guidance for SARS-CoV-2, issuing interim recommendations in July 2020 (WHO, 2020) and a subsequent global analysis in 2022 addressing pandemic-related waste generation, systemic deficiencies, and public health risks (WHO, 2022). The WHO also established the first comprehensive classification of medical waste, categorizing it into hazardous and non-hazardous types, with further subcategories such as infectious, sharps, pathological, pharmaceutical, chemical, and radioactive waste (WHO, 2024).

International organizations, such as the United Nations Environment Programme (UNEP), and various national regulatory bodies have further refined these classifications to improve waste management efficiency and sustainability (UN Environment Programme).

Table 2 outlines the classification of medical waste, pre-treatment requirements, and recommended disposal methods, providing a comprehensive framework for waste management during the COVID-19 pandemic (Behera, 2021). The table demonstrates that the handling and disposal procedures vary considerably depending on the type of material and its potential infectious risk. For several waste categories, pre-treatment was not required prior to final processing. According to the WHO guidelines, medical waste should be stored in a refrigerated area (3–8°C) if kept for up to a week. Without refrigeration, infectious waste must be disposed of within 72 h in winter and 48 h in summer in temperate climates, whereas in hotter regions, the storage time is limited to 48 h in cool seasons and 24 h in hot seasons (WaterAid, 2024).

Table 2. Classification, Pre-treatment Requirements, and Disposal Methods of Medical Waste (Behera, 2021).

Waste classification	Instances	Pre-treatment requirement	Terminal disposal method
Personal protective equipment	Face mask, medical gown, safety caps, goggles etc.	Not required	Incineration
Liquid waste	Body fluids, discarded disinfectants, infected secretions, liquids from laboratories and floor washing etc.	Separate waste gathering system linked to effluent treatment process	Pre-treatment before mixing with another wastewater

Contaminated waste	Blood contaminated items, body fluids (dressings), cotton swabs, plaster casts etc.	Not required	Incineration or deep burial
Sharp waste	Needles, scalpels, blades, syringes (with fixed needles) etc.	Not required	Autoclaving or Dry Heat Sterilization followed by mutilation, shredding, encapsulation or treatment and storage in specialized facilities.
Microbiological waste	Cultures, specimen, blood bag, stocks, vaccine etc.	Sterilization, autoclave, microwave or hydroclave	Incineration
Contaminated textiles/fabrics	Bed linens, mattresses, beddings contaminated with body fluids or blood etc.	Not required	Disinfection followed by incineration
Waste generated from disposable items	Catheters, gloves, syringes, tubing, intravenous tubes and sets, urine bags etc.	Not required	Autoclave or shredding followed by recycling

Glass waste	Broken or discarded and contaminated glass, vials, ampoules etc.	Not required	Disinfection followed by incineration

Additionally, the WHO established a color-coded system for waste segregation (Table 3) to ensure consistency in disposal practices worldwide (WHO, 2017). Each color represents a specific type of medical residue. Waste from COVID-19 care, especially infectious and sharp waste, must be managed using strict protocols, including high-temperature incineration or autoclaving. Manual chemical disinfection is discouraged due to its inefficiency. Waste should not be mixed; general waste must be collected separately from hazardous waste, and COVID-19-related waste must be securely contained for safe transport (WaterAid, 2024, WHO, 2017).

Table 3. WHO color coding of waste (WHO, 2017).

Color	**Waste**
Yellow	Infectious, pathological and sharp objects
Brown	Chemical and pharmaceutical substances
Black	General, non-infectious waste
Lead container (without color)	Radioactive

At the national level, healthcare waste regulations further enhance safety. For instance, South African National Standards (SANS) mandate waste minimization, segregation, secure packaging, and disposal by accredited providers (South African Government, 2013). UNEP also introduced the three-S strategy - sorting, segregation, and storage (Capoor and Parida, 2021). By implementing these guidelines and regulations, international and national organizations aim to create a safer and more efficient medical waste management system, minimizing environmental and health risks. Although organizations such as WHO provide comprehensive frameworks, these guidelines remain legally non-binding. Therefore, the mandate for enforcement and penalty imposition shifts entirely to national authorities, as SANS has demonstrated. These regulations outline facility responsibilities, including a mandatory annual audit by an appointed management officer, while leaving specific penal measures to be determined by national legislation (South African Government, 2013). In Pakistan, the enforcement of Hospital Waste Management Rules 2005 within health facilities falls under the Department of Health. If hazardous waste is found outside a health facility, the Environmental Protection Agency takes action. The legal framework includes provisions for penalties and other procedures to ensure compliance (Zeeshan et al., 2005).

In Poland, the WHO's 2020 COVID-19 waste management guidelines were integrated into national regulations by the Ministry of Health. These guidelines recommended the safe handling of COVID-19-related waste, including PPE and contaminated materials, by separating it from other waste and treating it through incineration or autoclaving. The guidelines emphasized using PPE for waste handlers and secure storage methods (WHO, 2024; Minister of Climate and the Chief Sanitary Inspectorate (Poland), 2020).

Overall, while international organizations provide guidelines for medical waste management, enforcement mechanisms, monitoring, and penalties for non-compliance are established at the national or regional level, varying according to local laws and regulations.

Conclusions

The COVID-19 pandemic led to a significant increase in medical waste production. In the interest of public health, environmental concerns were temporarily deprioritized. The production of medical waste increased significantly, especially non-infectious waste such as PPE (Shams et al., 2021; Haque et al., 2021; Joseph et al., 2021).

The impact of the pandemic varied across countries. For instance, in the USA in 2021 the demand for face shields increased by 300% (Behera, 2021; Haque et al., 2021). Similarly, a pronounced surge in PPE demand was observed in Canada, Brazil, China, France and Japan

(Shams et al., 2021; Statistics Canada; Haque et al., 2021; Parashar and Hait, 2021; Khan et al., 2023; Silva et al., 2020). Although cross-country data vary due to differences in waste management systems and limited reporting, the COVID-19 pandemic significantly accelerated global medical waste generation, reaching levels projected for the 2040s under normal conditions (Shams et al., 2021; Hanedar et al., 2022).

The increased demand for medical products and improper waste management, and inadequate guidelines for handling infectious materials resulted in significant environmental challenges. These included air, water and soil pollution, negative impact on the ecosystem, increased exposure to harmful pathogens, and a higher risk of infection and secondary COVID-19 transmission (Haque et al., 2021; Yousefi et al., 2021; Sangkham, 2020; Zand and Heir, 2020). Garbage disposal processes generate greenhouse and toxic gases, metals and dioxins that contaminate the environmental compartments and food chains (Zakaria et al., 2005; Ye et al., 2022). Each type of medical waste should be treated and disposed of using specific methods that minimize negative effects. Proper storage of waste, its classification and color coding are also important. Public awareness campaigns should be conducted to educate society on how to safely handle day-to-day PPE and accredited providers should undergo regular employee training on the most recent guidelines. In more severe cases, penalties should be taken into consideration (WaterAid, 2024; WHO, 2017).

The dramatic rise in medical waste during the COVID-19 pandemic has underscored critical deficiencies in global waste management strategies. Further research is necessary to implement life-cycle assessment of biodegradable and recyclable PPE materials, optimize advanced treatment technologies such as autoclaving, and design proactive logistics models capable of anticipating waste generation during public health crises.

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