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Global Perspectives on Healthcare Waste Management and Bibliographic Mapping during the Crises of COVID-19

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Abstract

The lack of proper waste management of health care facilities can have a significant negative health impact on the global population. This study provides a critical view on the current state of the existing healthcare waste management practices used in healthcare facilities around the world during the Coronavirus disease 2019 (COVID-19) pandemic outbreak. The increasing amount of COVID-related healthcare waste was analyzed and classified to provide justification for the urgent need to develop waste management standards that ensure safe containment and diversion of hazardous and non-hazardous wastes through recycling, reuse and repurposing. The waste handling, treatment, and disposal management of healthcare waste from various COVID-infected locations such as homes, quarantine centers, camps, and hospitals have been reviewed. A total of 100 documents on COVID-19 related healthcare waste were published on the Web of Science database over the 2020-2022 period. Innovative solutions for effective waste treatment and disposal, related government policies and regulations, and literature survey supported by VOSviewer-aided detailed bibliographic analysis are presented and critically discussed. Thus, the present research output advocates for a paradigm shift towards circular economy principles in healthcare waste management, emphasizing waste reduction, recycling, and recovery, and encourages global cooperation to develop resilient, crisis-responsive waste management systems.

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Introduction

The COVID-19 is caused by severe acute respiratory and identified in Wuhan, China in December, 2019 [1–3]. The virus has spread world-wide, and has been declared a Public Health Emergency of International Concern (PHEIC) by the World Health Organization (WHO) [4]. Historically, it remains a major pandemic danger around the globe. The statistical report from August 2022 showed reads 590 million infected cases and 6.4 million death cases (https://www.worldometers.info/coronavirus/) where the world's leader USA remains on top of the list for infected cases (>94 millions), death cases (>1 million) and recovery cases (>89 millions) [5]. SARS-CoV-2 has high transmittable nature and hence a significant number of COVID-19 patients were hospitalised. Transmission of this virus can be done through droplets, aerosols, and direct or close contact through secretions or fomites [6]. Current studies revealed that the coronavirus is highly infectious and has a high survival rate of nine days on material surfaces (such as plastic, glass, and metals) [7]. This necessitates the implementation of strict infection-prevention techniques and measures to protect healthcare workers and patients [8]. Personal protective equipment (PPE) are used extensively in both everyday human life and medical care to minimize the risk of transmission of the virus between patients and healthcare providers [8–9]. As a result, inevitably and rapidly increase in health-care wastes (HCWs). In turn, this poses a danger of escalating the virus spread which calls for a proper handling of the HCWs [10]. Since the start of the pandemic, the HCW volume has increased nearly 600 times [11]. Based on data from July 31, 2020, 8,055 t d^{-1} were produced by USA alone, followed by Brazil (2,774 t d^{-1}), and India (2,160 t d^{-1}) [12]. High amounts of HCW were accumulated throughout the world, including countries like Iran, Pakistan, Saudi Arabia, Bangladesh, and Turkey. Based on the problems of waste management, the present paper has raised a scope for geographic coverage of COVID-19 healthcare waste generation during the peak period of COVID-19 pandemic (2020–2022) in terms of different types of waste generation, treatment and disposal managements, lawful regulations, and technological innovations covering circular economic impact on social and environmental life. The issues, challenges and regulatory guidelines related to the pandemic outbreak are also discussed. This paper also discusses the cumulative information of research focus and articles published for the mitigation strategies for HCWM from web of science as a scientific database. The expected benefits of this study on global healthcare waste management during COVID-19 provides insights for sustainable practices, policy improvements, and resilience building, ultimately protecting public health, environment, and economies. The final outcome of these findings and recommendations contribute to achieving United Nations' sustainable development goals (SDGs) and foster global cooperation and knowledge sharing.

1) Healthcare waste (HCW)

The HCW, formally referred to as bio-medical waste (BMW), is generated mainly during the medical treatment of patients in hospitals and at research laboratories, and includes any waste generated during healthcare activities. It is the second most dangerous waste on the planet after radioactive waste. Every year, at least 5.2 million deaths are attributed to improperly managed medical waste, including 4 million children [13] and nearly 25% of all diseases are due to mismanagement of HCW [14]. Wastes from sharp objects, human body parts, blood, chemicals, pharmaceuticals and medical devices constitute hazardous or non-hazardous waste [10]. The majority of this garbage is from medicare institutions, labs, morgues, necropsy centers, perfusions, convalescent homes, hospitals or infirmary [15]. Wastes are produced at different stages of immunization, diagnostic procedures, treatment, medical studies, manufacturing or testing of biologicals in humans or animals. Improper waste management are associated with serious consequences for humans [16]. In the case of an outbreak of an infectious disease, there is a rise in trash generated by healthcare facilities and as a result, management must take extra steps to avoid unfavorable repercussions [17]. The amount of healthcare waste generated from COVID-19 since the outbreak was about 2.6 million tons per day worldwide [18]. A danger of immediate infection exists due to exposure to contaminated trash by waste management employees and frontline professionals like physicians and nurses [19].

In general, the HCW is characterized according to radioactivity, presence of infectious compounds, sharps, genotoxicity, cytotoxicity, and biologically aggressive medicines [20]. The most commonly collected HCWs from hospitals are divided into five groups: 1) sharps waste; 2) tissues waste; 3) infectious waste; 4) chemical waste; and 5) medicine waste [21]. HWC is mostly constant when it is under some type of conditions [22]. As COVID-19 is highly infectious and strongly survivable, municipal solid wastes (MSWs) have acquired an enhanced ability of infectiousness during the outbreak of the disease. For safety measures several forms of disposable materials were used which resultant into generation of HCW which was very risky for the transmission of virus [8, 23-24]. Therefore, all wastes from different hospital locations must be safely collected, transported, stored and then be also treated/ disposed off [25].

2) Classification of HCW

The solid waste composition analyzed over the pandemic period was similar to that produced during the normal health care operations with the exception of a large number of micro-plastics or plastics in the waste. There are eight classes of HCW as classified by WHO: infectious, sharps, general, chemical, pathological, radioactive, and pressurized containers. As per the "Biomedical Waste Management & Handling Rules" from 1998, the HCW was categorized into ten different classes: human anatomical waste, animal, sharps, micro-biology, biotechnology, liquid, unwanted medicines and cytotoxic drugs, chemical, soiled, and incineration ash. In 2016, the HCW categories were reduced to four, each with a different color red, blue, white, and yellow, as guided by the

"Biomedical Waste Management Rules". The red color-coded category included contaminated but recyclable waste containing non-chlorinated plastic containers; the blue coded class refers to medical glassware and utensils; white - for shape waste, and yellow - for most of the HCW including pathological waste, infectious waste, medical chemical waste, clinical lab waste and pharmaceutical waste (expired drugs and medicines). Solid waste has vital components as observed in normal circumstances as it shows the possibility of the waste to be recycled and also to be managed sustainably, this was an important concept during the pandemic [10]. Figure 1 shows a list of hazardous items generated during the COVID-19 pandemic outbreak.

2.1) Hazardous HCW

Hazardous HCW types include chemical, pathological, radioactive, sharps and pharmaceutical waste.

- Chemical waste

Health facilities are a major consumer of chemicals; hence, the chemical waste that comes from these facilities strongly impacts the environment and health. Chemical waste, such as laboratory reagents, expired or unused disinfectants, film developing reagents, solvents and wastes that contain heavy metals such as broken thermometers, blood pressure gauges, and batteries are all referred to as healthcare chemical waste [26]. There have been some serious health concerns that have led to substitution of harmful substances with less harmful ones and adoption of cautious management strategies. There are many facilities utilizing hazardous chemicals that lack good administration in both developing and developed countries. During COVID-19, more than 140 million test kits were shipped worldwide, with a potential to generate 7,31,000 litres of chemical waste which is equivalent to one third of the volume of an Olympic-size swimming pool [27].

- Infectious waste

Healthcare infectious waste is any material contaminated with body fluids, laboratory cultures, tissues, and human excreta containing infective bacteria that can cause diseases, incidence and progression [26, 28]. Blood, swab, body fluids (urine, feces, vomit), and disposable medical devices are some of the infectious wastes. The use of personal protective equipment (PPE), which includes face shields, masks, boots, gloves, long-sleeved gowns, goggles, has greatly risen during the COVID-19 epidemic period [10]. Because of this, controlling the PPE-generated trash during a pandemic has become challenging [29].

- Sharp waste

Sharp waste includes used or infected syringes, discarded needles, blades, scalpels, knives, contaminated glass, certain plastic materials, etc. and are classified as bio-hazardous waste. Sharp waste poses blood related infection and is a major public health concern. A white color-coded container should be used to collect all sharp trash [30].

- Pathological waste

Pathological non-anatomical waste includes body fluids, containers, and utensils that are generally used during surgery. This waste is comparable to the infectious waste, and its management during the current pandemic is of great importance. It can disseminate contamination akin biohazard waste because it contains viral particles of an infective nature [31]. This waste is causative of biological hazards of infectious diseases (HIV, hepatitis, tuberculosis), physical hazards (cut injuries, accidental fires, radiation) and even chemical hazards (formaldehyde, xylene, methacrylates, aromatic amines, glutaraldehyde, latex).

- Pharmaceutical waste

Biopharmaceutical waste is typically produced in hospitals, pharmacies, and distribution centers. Examples of pharmaceutical wastes include contaminated medicines used in percutaneous patches, biological products for treatment and in vaccinations [32]. Medicinal trash, on the other hand, includes expired and contaminated pharmaceutical items [26].

- Radioactive waste

Due to high efficiency in diagnostics and therapeutic applications, the radioactive isotope usage has significantly increased. The radioisotopes used are ^{14}C (carbon14), ^{99m}Tc (technetium 99m), ^{18}F (fluorine 18), ^{123}I, ^{125}I, ^{131}I (iodine-123, 125, 131) and ^{3}H (tritium) and is categorized under nuclear medicine. As per data from International Atomic Energy Agency (IAEA), isotopes are used in 134 out of 195 countries (69%) for heart scan (myocardial perfusion and radionuclide angiography) and other diagnostic studies. Though the number of isotopes used are laser but its disposal mismanagement may result in serious complication of health and the environment.

2.2) Non-hazardous HCW

Non-biological, non-chemical and radiologically inactive materials are considered as non-hazardous waste. This waste includes newspapers, magazines, used plastic bottles, office papers and covers of packaged foods. Non-hazardous trash can be compared to household waste and is recycled in a more sustainable manner. Non-hazardous HCW is generated from various symptomatic and asymptomatic patients by their day-to-day activities [33]. During COVID-19, more than 140 million test kits were shipped worldwide, with a potential to generate 2,600 tons of plastic waste [27]. Approximately 97% of that plastic waste was incinerated which created an additional pollution burden on the existing waste management systems.

2.3) Other types (Test kits)

Another kind of garbage dissipated in significant numbers during COVID-19 epidemic is that from various detecting procedures, as prevalence and global transmission have increased the need to detect infections and aid in quarantine measures and social distancing. It is mandatory for each test kit to be used only once and so this adds to the waste stream. If not treated appropriately, this waste could get contaminated and contribute to the spread of the virus.

Handling of HCW

For prevention of health problems and recovery of material, appropriate handling of HCW is necessary at the source. Its proper storage and transportation are also required for maintenance of resource efficiency. Preference can be given to existing protocols of HCWM for controlling of waste in the pandemic situation. However, precaution should be taken as COVID-19 has transmitted easily. Waste collection, segregation, storage, and transportation are the main methods for current waste handling in COVID-19. The infectious healthcare waste generated from home (face masks, wipes, tissues), quarantine centers/ camps (waste food, disposable utensils, water bottles, kitchen waste, packaging material, waste papers, waste plastics, dust) and hospitals (color-coded bins, bags) were handled as per the instructions of Central Pollution Control Board (CPCB, 2020) and Chand et al. [34] with proper disinfection using 0.5% chlorine-based disinfectants or 1% hypochlorite solution.

1) Collection

Collection of waste is an important step of waste handling, with proper care and risk-free disposal of both hazardous and non-hazardous waste. Contagious COVID related waste is collected aper the local and national guidelines of waste handling [30] into designated containers. For example, sharp materials are collected in safe boxes, infectious materials in specific color-coded bags/ containers labeled accordingly with hazardous symbols. The collection of non-hazardous material is categorized according to the type of waste which helps prevent the risk of exposure and minimizes the amount of hazardous material.

2) Segregation

The separation of waste in appropriate containers is referred to as segregation. The aim of segregation is to group the hazardous and non-hazardous HCW and facilitate disposal [35]. Waste segregation is a major component of waste management at healthcare facilities and scientific laboratories. Color codes have been assigned to enable easy segregation of waste and proper disposal procedures. To separate infectious waste, clearly designated containers with the type and weight of the trash are utilized. Infectious trash is usually maintained in plastic bags that are lined with polyethylene, boxes made of cardboard, or other leak-proof containers. To distinguish between different sorts of waste, color-coding is used. Prior to disposal, infectious waste, chemical waste, pharmaceutical waste, metallic or other types of waste should be sorted out in color-coded containers.

3) Storage

After segregation, moving of HCW bins, bags to either temporary or permanent storage is very equally important. COVID-19 waste should be stored separately for more than 24 hours in a temporary storage location. It should also be sent as soon as feasible to a garbage disposal supplier. The public-access protected area should be used as a storage facility. Refrigerators, freezers, and protective devices should be utilized to store biomedical waste in particular. The storage facility must be sanitized on regular basis with proper maintenance of constant temperate [36]. Most importantly, use of small or disposal container are preferable to avoid the spill and lifting problems and if the container used are metallic or plastic based then its disinfection process need to on place and followed regularly [37].

4) Transportation

A closed medical waste transfer trolley is used to convey the bagged COVID-19 trash to a temporary storage location or treatment zone. Waste should be transported in a vehicle that is well-protected and secure. Arrangements for a separate vehicle to collect and transfer the rubbish should be made. Specialized trolleys/ carts are utilized to collect the garbage, and that every trip collecting biomedical waste from home care/home quarantine/hospital is sanitized with one percent sodium hypochlorite solution. Transportation might be a temporary storage near hospitals or long-distance storage for final disposal at a municipal HCW center. Sanitization process for vans, drivers, and their routes were followed in many places along with a tracking system during

COVID-19 pandemic [11]. Full training and induction to safe practices (cleaning, hygienic) were given to all waste handling transporters during each stage of risks [38].

4.1) In-house transport and storage

In-house transport and storage of HCW is a place close to a hospital where the HCW is transported in the shortest and unexposed route for a temporary storage or disposal. The necessary precautions need to be taken in terms of use of PPE and safety measures by transporters (staff, driver, facility in-charge). The storage must be cleaned and sanitised regularly, well ventilated, inaccessible to vertebrate pests, and of restricted access from the public. Overall, prevention of exposure and transmission of infections need to be avoided.

4.2) Transportation to offsite treatment

Transportation to offsite treatment implies that the HCW is carried from the concerned healthcare facilities to treatment facilities by a same rout of public transportation. Collection and transportation of HCW can be performed with regular workers and specialised worker (licensed HCW service supplier) when necessary. If hazardous waste is transported internationally via sea for treatment purposes, it should follow the nation's regulations and international agreements [39]. If a national regulatory policy is not in place, then the recommendations for transportation of harmful goods as published by the United Nations [40] should be followed.

Treatment of HCW

Managing HCW throughout this pandemic has been seen to be different and rather unique in every country [41]. As expressed by WHO, 85% of HCW are non-hazardous, though 10% are infectious and 5% hazardous wastes [17]. HCW waste must be properly handled to avoid environmental contamination and the spread of infectious diseases [42] otherwise 10-25% of hazardous wastes are most dangerous to spread of infections [43]. The UN Human Rights Council recommends that the methods used in the disposal of HCW must be improved to avoid bad effects that come with improper handling of waste. HCW is associated with risk of negative impact on human health, exposure to emissions of highly toxic gases during incineration, and health risks associated via direct contact with HCW. The HCW during this pandemic has been shown to be a major concern [44-48], as it poses a rise in the risk of further contamination through different pathways. Safe handling, disposal of waste and treatment must be prioritized for reducing contamination of air, water and land to curb the increase in generation in BMW [20]. Hence, decontamination, destroying or disinfection of the infectious bio-wastes necessitates effective treatment of HCW through autoclaving, gasification, pyrolysis including plasma pyrolysis, chemical disinfectants, and microwave irradiation.

1) Autoclaves

Autoclaving is a form of a heat treatment process for sterilization that is based on the principle of use of a standard pressure cooker. The autoclave treatment method can effectively treat categories of waste such as soiled, solid wastes, sharps blood microbiology and biotechnology waste. Autoclaves operate with steam under pressure using intense heat of about 121°C for 30 min under 15 psi. The interaction between the high temperature steam produced in the autoclave and the waste material destroys the microorganisms present in the waste. There are three commercially available types of autoclaves, and these are pre-vacuum type, gravity types and retort type [49-50]. The gravity type autoclave which pumps steam into autoclave chamber containing ambient air. The pre-vacuum type autoclave uses vacuum pumps to get rid of air with a reduced time cycle of 30–60 minutes at 132 °C. Retort autoclaves are manufactured with the purpose of achieving very higher pressure and temperature for destruction of the infectants. According to WHO standards for the Novel corona virus (2019-ncov), biosafety levels BSC-2 and BSC-3 will be necessary to safely handle COVID-19 starting on February 12, 2022. System autoclaves are excellently suited to meet the WHO's safety criteria.

2) Microwave

Microwave technique operated at 177-540°C temperatures and is based on reverse polymerization process where direct application of high-energy microwaves to organic matters to breakdown the material into simpler chemicals. Microwave-assisted pyrolysis (RP) is a high-lead pyrolysis method for infectious metals and plastic trash with pathogen inactivation. The RP systems could achieve 80% volumetric reduction. Furthermore, sterilized RP wastes are comparably stable and suitable for sanitary landfill disposal after shredding. The main advantages of microwave technologies are lower energy input, limited heat loss and lower toxic residue in the environment. Microwave was found to be the most successful on-site disinfection method to achieve maxi-mum disinfection of viruses as reported by Chinese Ministry of Ecology and Environment [48]. Compared to autoclaving, the onsite microwave disinfection is more efficient, cost effective, eco-friendly, and leads to time savings and spread risk prevention [51].

3) Pyrolysis

Pyrolysis is a process of treating bio-waste decomposition with high heating temperatures (540–830°C) and includes pyrolysis-oxidation, induction-based pyrolysis, plasma pyrolysis, and laser-based pyrolysis. There is emission of gases (carbon monoxide, ethane, ethane and hydrogen), liquids (tar and oil), and solids (char and carbon black) during the heating process. The gases can be stored or purified to be used as fuel for heating the radiant tubes. Since metals cannot be de-composed at that temperature, metallic components have to be separated before bio-waste pyrolysis. Due to the emergency of rapid spread of COVID pandemic, plasma energy was also used to rapidly decompose waste [48]. This method proved very efficient for 95% emission reduction and 90% waste mass reduction [31].

4) Chemical Disinfection

Chemical disinfection is one of the most effective ways to minimize the harmful organisms that cause infectious disease transmission. Simple cleaning, sterilization, and the use of chemical disinfectants such as sanitizers, biocides and. antiseptics, are all examples of cleaning and disinfection processes. A good disinfectant should be able to kill a wide variety of microorganisms and germs. It should have chemical and surface compatibility, non-toxicity, simple water solubility, non-flammability, pleasant odor, cleaning ability, and be cost effective. To disinfect medicare facilities, a variety of chemical agents are available. Oxidizing agents, alkali, acids, alcohols, halogens (hypochlorite and iodine-based iodophors), aldehydes, biguanides, phenolics, and quaternary ammonium compounds are the nine broad groups of liquid-based chemical disinfectants [50,52]. Hydrogen peroxide-silver nitrate products, accelerated hydrogen peroxide products, and quaternary ammonium compounds/glutaraldehyde, or formaldehyde combinations have recently been demonstrated to be effective as disinfectants, with no-touch approaches of surface decontamination technologies, dry-mist, or vapor fogging method used.

5) Ultraviolet irradiation (UVI)

UVI attracted huge attention for disinfection of air and surfaces. UVI has been used as an alternative to the chemical based disinfectant chloroxylenol is generally preferred for disinfection of utensils or floor surfaced bacteria and viruses. Although many reports were available on UVI systems and products during COVID-19, very few showed validation data of time dependent log removal of viruses. Reports suggested effective doses of 20-40 mJ cm^{-2} at 254 nm, and 37.5 mJ cm^{-2} at 280 nm, respectively [53-54].

6) Encapsulation and inertization

When no other option is possible or accessible, hazardous waste can be placed in metallic drums, sealed with polyethylene foam, and dumped in landfills. This approach is deemed appropriate for disposal of pharmaceutical or chemical waste [55].

Disposal of HCW

Minimizing or totally eradicating hazardous waste is one of the main objectives of HCWM. HCW generated during COVID-19 pandemic should be treated according to local guidelines and regulations [24, 38]. Many reports are available for managements of these wastes in different countries including Iran, Egypt, Jordan, Mauritius, Brazil, India, Turkey, USA, Mongolia, and UK ([13, 56-58]. However, in countries like Iran and India, insufficient waste treatment facilities, protective precautions, and personal training existed [59]. It was also reported that ~15-35% of the waste generated by the hospitals are infectious wastes [17]. Different countries have implemented various policies for the management of medical wastes generated from household, quarantine, hospitals facilities in the COVID-19 era [41]. Spreading of infectious waste and environmental pollution occurred if waste was not properly managed [42]. The disposal practices are discussed as below.

1) Incineration method

Incineration is a waste treatment procedure that involves burning or igniting organic waste at high temperatures. Incineration is used to treat trash from research institutes, chemical businesses, pharmaceuticals and hospitals, in particular in distinct regional zones. The incineration process converts waste into ashes, heat, and flue gases that can be used as energy for other operations, such as electricity generation [60]. Incineration can reduce the mass of waste in landfills by 95-96 %. Due to the reduced carbon footprint, there is an increased interest and demand for energy produced in incineration facilities in Sweden, Japan, and Germany [50]. Incomplete waste destruction, dioxins emissions and inappropriate ash disposal are a result of improper or lack of operation in small scale incinerators, which are 40,000 times higher than emission limits set on Stockholm Convention [61].

2) Landfills

Sanitary landfills, open dumps and landfills are three options for disposing of treated and untreated garbage. Mixed and untreated solid wastes are dumped in uncovered regions in open dumps. The open dumps however become a breeding ground for a variety of flies and insects that can spread infectious diseases. During the rainy season, the dumps flow off and contaminate the air, ground water, and surrounding soil. As a result, many Indian cities, such as Bilaspur, have eliminated open dumps. Landfills are usually found in urban areas and are used to dump large amounts of solid waste into a hole. Every day, a layer of soil is placed on top of the pit to prevent insects and flies from breeding. After a period, trash in dumped landfills is tightly crushed into cells and covered with a thick layer of soil. In the near future, this type of landfill will be repurposed as a parking lot or park. Landfills suffer from leachates and groundwater contamination. Alternatives to landfills include sanitary landfills [50] which can, to some extent, solve the leaching problem. To prevent liquid spills, the pits are coated or sealed with non-permeable materials, such as clays and plastics. This landfilling method is more expensive than the other two, but it has a faster rate of waste degradation owing to the lack of oxygen. With the advancement in science and technology, some safe and secure landfilling of HCW suggests segregation of infectious and non-infectious waste, use of absorbent material to minimize liquid waste using some emerging technologies of bioreactor landfilling for waste stabilization followed by plasma gasification and advanced leachate treatment for waste to energy conversion [62].

3) Recycling and composting

The non-hazardous waste is a sustainable material that can be collected, reused, recycled and/or composted. Recycling is the processing of a waste to another value-added product and contributes to waste reduction and diversion. The recycling can be carried out by composting of food, garden, paper, and other organic waste materials. Some of the benefits of recycling and composting include reduction of greenhouse gas (GHG) emissions, prevention of air and water pollution, supply of reprocessed raw materials, energy savings, and conservation of natural resources [63].

Hence complete eradication of COVID-19 virus, is the top most priority from all surfaces of both COVID-19 HCW and non-COVID-19 HCW. Some innovations and startup provided ozone and plasm pyrolysis-based treatment solutions for the disposal of pandemic waste [55].

Statistics of HCW during COVID-19

1) HCW items

COVID-19 pandemic has led to a massive HCW generation (Figure 1). The items that contributed to HCW are categorized into three wastes streams: non-hazardous, hazardous, and bio-hazardous waste. The non-hazardous waste includes organic-rich materials, such as biodegradable (waste food, tissue paper, garden waste) and recyclable (newspaper, cardboards, books) waste. Examples of hazardous waste include disinfectants, pesticides, CFL blue, tube lights, batteries, etc. whereas the bio-hazardous materials may contain metal sharps (blades, disposable scalpels, vaccine needles, metallic implants, one-time-use empty oxygen cylinder cans) and glass sharps (vaccine vials, test tubes, broken glass vials, discarded vials, bottles, slides, petri plates). The major percentage of waste, which is highly regulated and cautious, is the infected and infectious waste (Figure 1). The infectious waste generated in the form of anatomical, chemical, soiled, and chemotherapy and laboratory items, discarded linen, medicines, PCR testing cartridges, gowns, masks, gloves, petri dishes, blood bags, etc. The infected waste contains syringes, wrappers, body bags, hair covers, shoe covers, surgical caps, disposable labcoats, test kit plastics, swabs, safety boxes, polyethylene bags, goggles, hand sanitizer liters, floor cleaner bottles, disinfectant bottles, hand wash bottles, plastic containers, etc. [64].

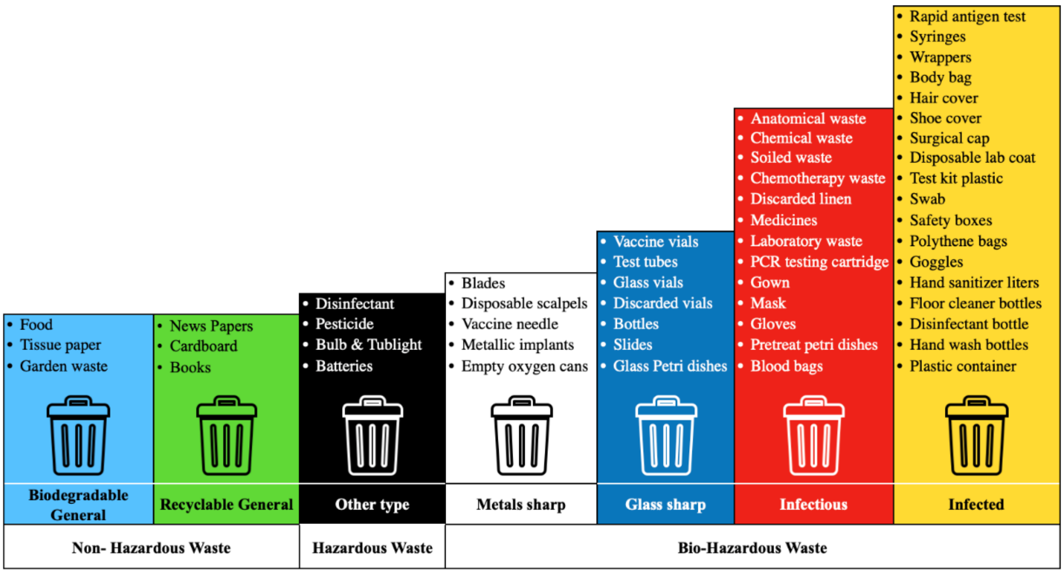


Figure 1 Waste with color-coded categorization generated during the COVID-19 pandemic outbreak.

2) Global hazardous HCW

During the first phase of COVID-19 situation, the infectious waste increased from 40 t d^{-1} to 240 t d^{-1} (600% increase) in the Hubei Province, People's Republic of China. In response, the Asian Development Bank (ADB) set a mathematic formula indicating a rate of 3.40 kg d^{-1} of hazardous waste generation by COVID-infected patients that takes into account the number of infected cases, death cases, and recovered cases. The calculation results of the estimated total hazardous waste are shown in Table 1. The world's total waste generation rate was 73,890.42 t d^{-1}, with major stakes of Asian territory (35.93%), Europe (29.40%), and North America (25.24%). The collective contribution of the South America, Africa and Ocean territories was only 9.45% of the total hazardous waste. The actual quantity of the total hazardous waste generation over a period of infection time is the multiple of the daily production rate and the number of days in that period [65]. Top 20 countries generating the maximum amount of hazardous waste are led by the USA with 17.87% contribution, followed by Japan (9.33%), South Korea (8.15%), Germany (6.10%) and Vietnam (6.04%). Interestingly, although China and India are highly populated countries and had numerous COVID-19 cases, they were not among the top 20 hazardous waste generating countries. The difference in the hazardous waste generation in different regions of the world is illustrated in Figure 2.

Table 1 Global distribution of COVID-19-generated hazardous waste per region and top 20 countries [5]

Territory	Infected cases	Death cases	Recovered cases	Total infected persons	Total hazardous waste (t d^{-1})	% Distribution
World	59,26,35,973	64,46,813	56,44,56,684	2,17,32,476	73,890.42	100.00
Asia	17,53,56,249	14,53,646	16,60,95,067	78,07,536	26,545.62	35.93
Europe	21,81,17,867	18,87,785	20,98,41,772	63,88,310	21,720.25	29.40
North America	11,20,13,114	15,10,961	10,50,17,775	54,84,378	18,646.89	25.24
South America	6,28,21,081	13,19,465	6,04,22,194	10,79,422	3,670.03	4.97
Africa	1,25,62,609	2,57,083	1,17,21,583	5,83,943	1,985.41	2.69
Oceania	1,17,64,332	17,858	1,13,57,587	3,88,887	1,322.22	1.79
Top 20 Countries						
USA	9,43,48,507	10,60,755	8,94,03,777	38,83,975	13,205.52	17.87
Japan	1,48,61,375	34,323	1,28,00,155	20,26,897	6,891.45	9.33
South Korea	2,09,83,169	25,441	1,91,86,231	17,71,497	6,023.09	8.15
Germany	3,14,39,645	1,45,394	2,99,69,000	13,25,251	4,505.85	6.10
Vietnam	1,13,53,573	43,095	99,97,136	13,13,342	4,465.36	6.04
Italy	2,14,00,179	1,73,571	2,02,56,778	9,69,830	3,297.42	4.46
France	3,41,44,969	1,52,910	3,31,86,440	8,05,619	2,739.10	3.71
Poland	61,09,621	1,16,737	53,35,875	6,57,009	2,233.83	3.02
Brazil	3,40,96,935	6,80,852	3,28,54,341	5,61,742	1,909.92	2.58
Mexico	68,90,549	3,28,525	60,87,871	4,74,153	1,612.12	2.18
Taiwan	48,24,550	9,342	43,76,964	4,38,244	1,490.03	2.02
Russia	1,87,96,472	3,82,954	1,80,89,941	3,23,577	1,100.16	1.49
Turkey	1,62,95,817	99,678	1,58,75,121	3,21,018	1,091.46	1.48
Spain	1,32,80,557	1,11,339	1,28,62,276	3,06,942	1,043.60	1.41
Honduras	4,46,454	10,952	1,32,498	3,03,004	1,030.21	1.39
Australia	97,37,319	12,655	94,42,311	2,82,353	960.00	1.30
U.K.	2,34,20,826	1,86,087	2,29,54,663	2,80,076	952.26	1.29
Turkey	1,62,95,817	99,678	1,58,75,121	3,21,018	1,091.46	1.48
Martinique	2,16,335	1,022	104	2,15,209	731.71	0.99
Guadeloupe	1,86,380	971	2,250	1,83,159	622.74	0.84
Iran	74,59,175	1,42,738	71,40,272	1,76,165	598.96	0.81

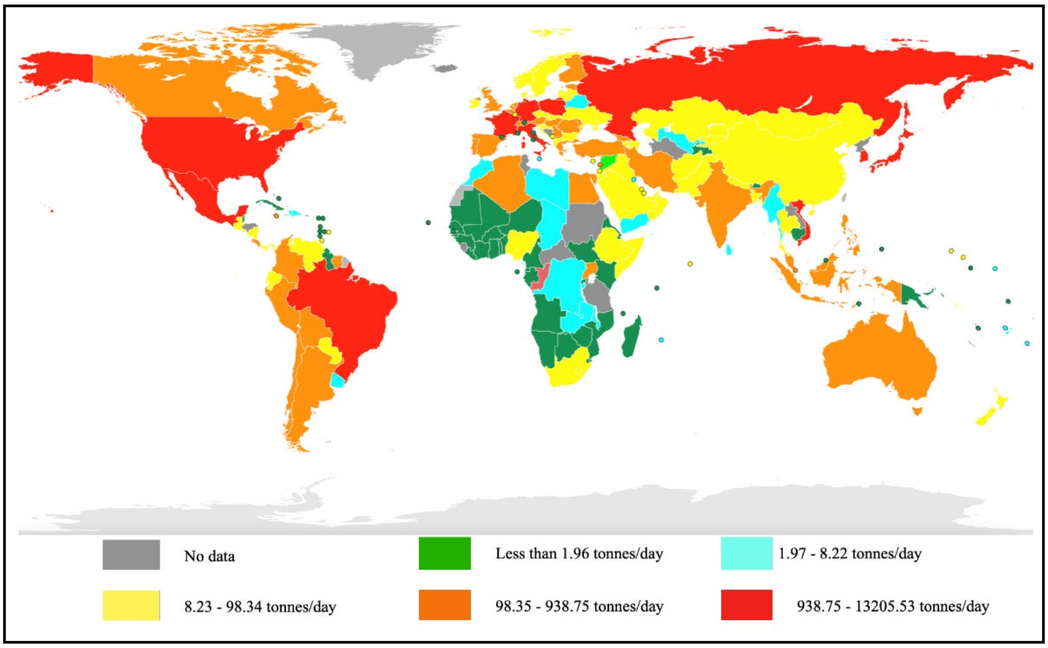


Figure 2 World map of COVID-19 hazardous waste generation in t d^{-1} [5].

3) Scientific contributions to COVID-related healthcare waste generation over 2020-2022

A search of the Web of Science (WOS) database for the period 2020-2022 was performed on August 17, 2022 using the following five sets of keywords: 1) "bio-medical waste" and "COVID"; 2) "biomedical waste" and "COVID"; 3) "healthcare waste" and "COVID"; 4) "health care waste" and "COVID"; and 5) "health-care waste" and "COVID". VOSviewer software (Version 1.6.18) was employed for visualization and analysis of the scientific landscape of the co-occurrence network maps. The analysis results are summarized in Table 2. A total of 100 documents related to the search keywords were found in the WOS. These documents were extracted from the following indexing databases: Science Citation Index-Expanded (73 documents), Social Sciences Citation Index (3 documents), Conference Proceedings Citation Index – Science (2 documents), and Emerging Sources Citation Index (22 documents). Year-wise, as of August 17, 2022, the number of documents published under WOS were 12, for 2020, 55, for 2021, and 33, for 2022.

Bibliographic data extracted from the WOS database often requires careful cleansing to rectify variations and errors. Discrepancies in publication record including names of author, publisher, journal, and year of publication, can compromise the accuracy of research analyses. To address these issues, a thorough data clearing process is essential. This involves standardizing names of authors, publishers, normalizing journals, and authenticating publication years. Moreover, duplicate records must be identified and merged or deleted, while missing data is imputed using reliable sources. By employing tools such as Excel, R, and Python, and leveraging resources like authority and journal title abbreviations, researchers can ensure the integrity of their bibliographic data. This rigorous data clearing process ultimately enhances the reliability of research findings, facilitating informed decision-making and contributing to the advancement of scholarly knowledge.

Table 2 Scientific contributions to COVID related healthcare waste in the WOS

Description	Results
Main information about data	
Time span	2020-2022
Total reports (journals, books, etc.)	100
Subject areas coverage	36
Languages	2 (English 99+ Malay 1)
Document types	
Articles	66
Review articles	27
Letters	2
Meeting abstracts	2
Proceeding papers	2
Editorial materials	1
Publication information	
Total keywords	517
Total authors	497
Total affiliation organizations	100
Total countries	41
Total publication titles (journals/ books)	67
Total publishers	32
Total research areas	23
Citations	
Times cited	1321
Average citations per item	13.21
h-index	17

A countrywide network visualization for co-authorship under WOS revealed participation from a total of 41 countries. The results presented here include only networks with a minimum of two documents per country. The distribution was based on 19 items that were grouped into 4 clusters: 1) Green cluster: India, China, Germany, South Korea, Turkey, Italy; 2) Red cluster: Malaysia, Saudi Arabia, Japan, England, Pakistan; 3) Blue cluster: Bangladesh, Australia, Canada, Iran; and 4) Yellow cluster: USA, Poland, Ghana. India contributed 50% of the total documents linking with other countries from the search results at a link strength of 61, except England, Pakistan, Canada and Iran (Figure 3).

3.1) Keyword networking

The keywords with the highest occurrence frequency were obtained from the WOS database and VOSviewer analysis of the word map and density visualization (Figure 4). Keyword networking hit 517 keywords under WOS with a minimum of 3 keywords occurrence frequency which met 47 threshold keywords. For each of the 47 keywords, the total strength of the co-occurrence link with other keywords was calculated. The keywords with the greatest total link strength were selected and categorized into 6 clusters of 305 links and a total link strength of 475. Each cluster had a dominant keyword. For example, cluster-1 (red) of COVID-19 with 42 links, total link strength 125 and occurrence frequency of 49; cluster-2 (green) of management with 35 links, total link strength 79 and occurrence frequency of 23; cluster-3 (light blue) of biomedical waste with 32 links, total link strength 62 and occurrence frequency of 19; cluster- 4 (yellow) of healthcare waste with 19 links, total link strength 28 and occurrence frequency of 11; cluster- 5 (purple) coronavirus with 15 links, total link strength 24 and occurrence frequency of 5; cluster- 6 (light blue) of biomedical waste management with 9 links, total link strength 15 and occurrence frequency of 6.

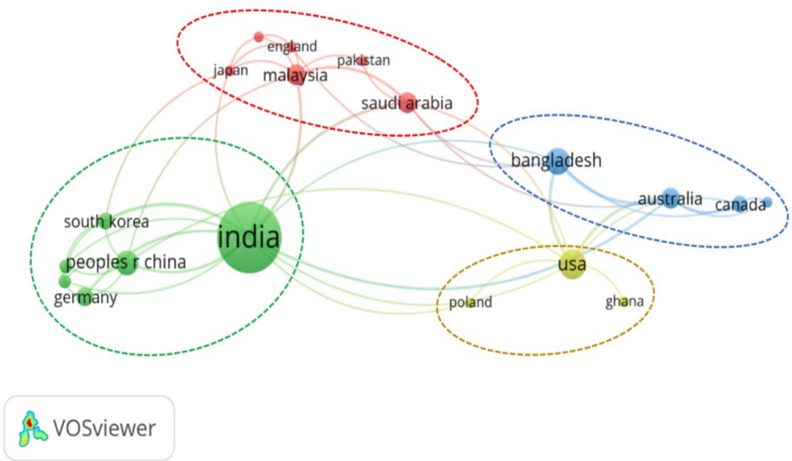
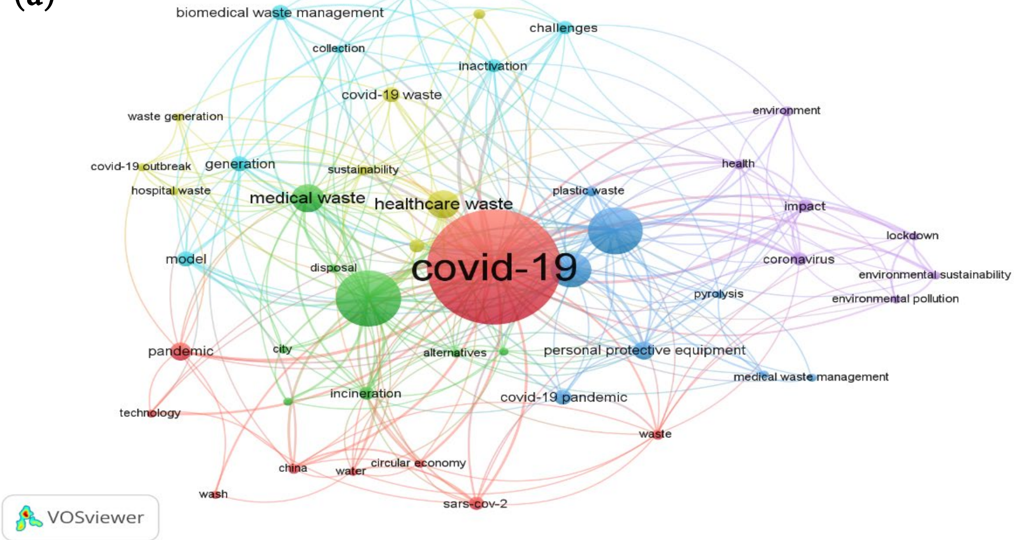


Figure 3 VOSViewer network of scientific contributions to COVID-19 related healthcare waste management by country.

(a)



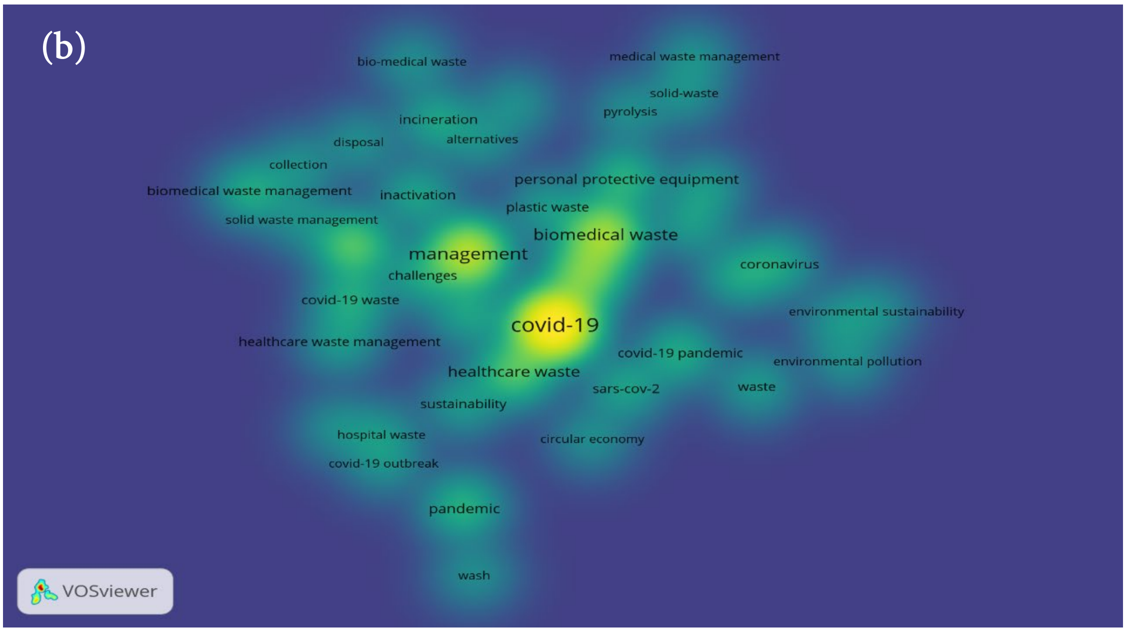


Figure 4 VOSviewer networking map analysis: a) word mining b) density visualization.

3.2) Data word cloud

World cloud was developed with an online world-art software (https://wordart.com) to provide information about the article type (what are the article types???.....), country of what???, publisher, authors and their affiliations, and research areas. Out of the 100 scientific contributions made to the topic of COVID-related healthcare waste generation, 66 documents were classified as research articles and 26 as review articles (Figure 5a). A total of 41 countries were represented in the published documents with a maximum hit of 155 times and a maximum occurrence of 50 times for India, followed by USA (11 times), Bangladesh (9), and China (8) (Figure 5b). A total of 497 researchers were listed as authors and co-authors. Out of that, 24 authors produced a maximum of 2 articles namely: Bodrud-doza M, Canepari A, Capoor MR, Chauhan A, Cotroneo A, Funicelli G, Garlasco J, Giacobone G, Gupta S, Jangre J, Kumar S, Lima RD, Mishra S, Ng KTW, Parida A, Patel D Prasad K, Rahman MM, Rao S, Shammi M, Singh B, Singh S, Thakur V, Torkayesh AE (Figure 5c). Altogether, 78% of the documents belong to the top 10 publishers, including Elsevier, Springer Nature, Sage, MDPI, Taylor & Francis, Thieme Medical Publishers, Wolters Kluwer Medknow Publications, Cureus Inc, Emerald Group Publishing, and American Chemical Society. Among these, Elsevier found to be the most recommended publisher with 34% of the documents, followed by 16% of the documents, for Springer Nature (Figure 5d). Major publication types are the scientific journal and total 67 different publication titles (journal names) are involved. with maximum 16% documents from Science of the Total Environment and Waste Management Research, followed by 6% Environmental Science and Pollution Research, 4% Heliyon, 3% Journal of Cleaner Production, 3% Resources Conservation and Recycling and 2% each from Chemosphere, cereus Journal of Medical Science, Environmental Research, International Journal of Environmental Research and Public Health, Journal of Environmental Management, Journal of Laboratory Physicians, and Sustainability (Figure 5e). The WOS search identified 23 major research areas for the 100 published documents (Figure 5f), with the top five being Environmental Sciences Ecology, Engineering, Public Environmental Occupational Health, Science Technology Other Topics, and General Internal Medicine. A total of 100 organizations were listed as authors' affiliations, with 34% of that coming from 10 organizations (8 from India and 2 from Malaysia): National Institute of Technology, Council of Scientific Industrial Research, Indian Institute of Technology, Jahangirnagar University, Bangladesh Rural Advancement Committee, CSIR National Environmental Engineering Research Institute, Indian Institute of Management, University Kebangsaan Malaysia, Vellore Institute of Technology and All India Institute of Medical Sciences (Figure 5g).

Figure 5 Word clouds of a) by article type, b) by country, c) by author, d) by publisher, e) by publication title, f) by research areas, g) by affiliations.

Innovative solutions

The COVID-19 pandemic affected every sector of life and environment. Due to the huge waste generation, existing waste management strategies and systems, including facilities and equipment, faced major challenges. This presented opportunities for some innovative thinking and waste management solutions [66]. There is a substantial need for innovations in order to address key challenges that are faced in waste plastic collection and also to integrate new technologies in segregating and treating existing waste management system due to limited availability of solutions. While the competence and efficacy of the old procedures and techniques are improved, innovations sustain the rise in garbage production. Some of the innovations were directed toward modifications per pandemic requirements and improvement in portable ventilators, oxygen generators, portable/ disposable oxygen cylinders, masks, PPE kits, face shields, etc. Beer and wine distilleries made innovative adjustments to their traditional operations to produce and distribute hand sanitizers at a fairly low cost and in a timely manner [67]. New startups were quickly introduced and joined the healthcare ecosystem for disinfection, equipment, handling and disposal of COVID related materials. For instance, startups in India, such as Aqoza Technologies (Ernakulam, Kerala) and PerSapien (New Delhi, Delhi) developed chemical-based disinfections and dispensing machines for public place disinfections. Despite the positive and persistent collective effort in waste management during the lockdown, an extra burden on the healthcare system globally was placed by the rapid accumulation of enormous amounts of non-degradable plastic waste. Considering the biodegradability issues with the use of plastics, it is today's challenge to develop renewable and biodegradable packaging materials, to which the European Union responded with the ban on the single-use plastics. Elsewhere, biodegradable masks and teabags from banana tree fibers and abaca are for example under development in the Philippines [68]. The PPE face mask plastic is recycled to 'Brick 2.0' by Eco Eclectic Technologies in Gujrat, India which convert the waste to value added product. The brick recycles about 52% of shredded PPE masks along with 45% paper sludge and 3% binder having great extent of fire resistant, waterproofing properties and coastwise very cheap of Rs 2.8 per piece (12×8×4 inches) containing 7 kg of biomedical waste per square feet [69]. With the advancement of science and technology, nanotechnology has emerged as a very efficient and fairly inexpensive tool for waste management of COVID-19 related environmental issues. For example, carbon nanotubes [70], zeolite- and metal-based nano-adsorbents can be used to disinfect and decontaminate SARS-CoV-2 containing solid and liquid waste as well as adsorb toxic organic compounds [71]. Nano-filters made from silver, zinc, bimetallic, and magnetic nano-particles [72] appear as a robust technology that maintain filtering efficiency and durability during wastewater treatment.

Government regulation and policies of HCW

National, local, and state governments who have healthcare trash operation plans and programs can greatly benefit from employing these plans and programs in their COVID-19 waste response. The benefits including the protection of health of healthcare workers, public and the environment, prevention of spreading of infectious diseases, reducing the risk of contamination, and healthcare cost reduction. When countries build their own policies, plans, or programs, they should incorporate contingency plans for pandemic scenarios, which can be developed based on the ongoing COVID-19 trash operation and related difficulties and challenges.

Worldwide, there are 168 public laws and policies that address or discuss healthcare waste management; whereas only 57 are related to medical waste and remaining 111 addresses other waste. The laws addressing a single waste sluice are generally more substantial than a law that astronomically covers several, with many exceptions. In several of the world's major metropolises, a decline in the mechanical recycling of plastics has been a notable consequence of COVID-19. For instance, in order to avoid toxic garbage in recycling centers, some major metropolises in the U.S. have temporarily ceased their recycling programs [73]. Due to the ongoing pandemic, the United States' recycling industry which was formerly emphasized by the Chinese sword policy of 2017, is facing multitudinous challenges [74]. While lower cosmopolises discontinued their pickup programs [73], many metropolises continued with their curbside collection services. The Organization for Economic Cooperation and Development (OECD) has assured that every major metropolis will provide garbage collection, they have also suggested a check of some of its recycling centers as the cases of COVID-19 harpoons.

In response to the coronavirus epidemic, the EU allocated 25 percent of its economic stimulus package to climate-friendly initiatives [75], while the South Korean government has vowed to reduce greenhouse gas emissions to zero by 2050 [76]. COVID-19 recovery poses both opportunities and dangers for increasing our resiliency to climate change and pollution from solid waste/plastic waste [77]. To mitigate the environmental pollution and prioritize the COVID-19 health and economic recovery programs, several global level forums have issued regulatory guidelines and some of them are listed in Table 3. The major and country specific organizations represented in most of the scientific reports and newspapers are: World Health Organization (Switzerland); United Nations (Kenya); Central Pollution Control Board (India), Ministry of Ecology and Environment, Health Commission of China (China); Illinois Environmental Protection Agency, California Department of Public Health, United Nations International (USA); European Commission, European Centre for Disease Prevention and Control (European Union); Sistema Nazionale per la Protezione dell'Ambiente (Italy); Ministry of Environment of South Korea, Ministry of Health and Welfare, United Nation Economic and Social Commission for Asia and the Pacific (South Korea); Ministry of the Environment Government of Japan (Japan); Swedish Environmental Protection Agency (Sweden); Department for Environment Food & Rural Affairs, Environment Agency (UK).

Table 3 COVID-19 related healthcare waste handling and disposal guidelines by different countries and agencies

No.	Country	Guidelines	Organization	Reference
1	Switzerland	Water, sanitation, hygiene, and waste management for SARS-CoV-2, the virus that causes COVID-19	World Health Organization	[78]
2	Kenya	Waste Management during the COVID-19 Pandemic: from response to recovery	United Nations Environment Programme	[79]
3	India	Guidelines for handling, treatment and disposal of waste generated during treatment/diagnosis/ quarantine of COVID-19 Patients	Central Pollution Control Board	[30]
4	China	The Ministry of Ecology and Environment issued Guide on management and technical on emergency treatment and disposal of medical waste caused by COVID-19 (Trial)	Ministry of Ecology and Environment	[80]
		Notice on environmental management of medical waste caused by COVID- 19	Health Commission of China	[81]
5	US	Proper disposal of personal protection equipment (PPE) at COVID-19 testing locations	Illinois Environmental Protection Agency	[82]
		Novel Coronavirus Disease 2019 (COVID-19) medical waste management - Interim guidelines	California Department of Public Health	[83]
		Water, sanitation, hygiene, and waste management for the COVID-19 virus: interim guidance	United Nations International Children's Emergency Fund	[84]
6	European Union	Waste management in the context of the coronavirus crisis	European Commission	[85]
		Infection prevention and control in the household management of people with suspected or confirmed coronavirus disease (COVID- 19)	European Centre for Disease Prevention and Control	[86]
7	Italy	CoViD-19 emergency: SNPA indications on waste management (English translated)	Sistema Nazionale per la Protezione dell'Ambiente	[87]
8	South Korea	Minister of Environment, Check the Management of Wastes Related to COVID-19	Ministry of Environment of South Korea	[88]
		The extraordinary measures for safety management of wastes telated to COVID-19 (3rd)	Ministry of Health and Welfare	[89]
		The safe waste treatment for COVID-19, lessons from the Republic of Korea	United Nation Economic and Social Commission for Asia and the Pacific	[90]
9	Japan	Guidelines for control on COVID-10 waste	Ministry of the Environment Government of Japan	[91]
10	Sweden	Waste management linked to the Coronavirus (English translated)	Swedish Environmental Protection Agency	[92]
11	UK	Guidance on prioritizing waste collection services during coronavirus (COVID-19) pandemic	Department for Environment Food and Rural Affairs	[93]
		Cleansing and PPE waste at a healthcare waste management facility: RPS C1	Environment Agency	[94]

Challenges of HCW

Operating COVID-19 waste is difficult and challenging because there is a need for an absolute end-to-end overhaul of the system. Management of the massive volumes of COVID-19 bio-medical garbage amidst fleetly changing standards and wide paranoia, while trying to prevent the spread of COVID-19 infection within the sanitarium has proven to be a redoubtable task [50]. The points below are of particular importance and relevance to handling biomedical waste.

a. Acceptable training in the environment of waste collection, trash isolation, trash bar-coding in applicable holders, and the necessity for social distancing must be given to anyone engaged in collection, isolation, movement, treatment, and discarding of biomedical waste.

b. The need to maintain hand cleanliness, using appropriate PPE, and using detergents in contagious counter blockade points/homes counter blockade units. Conservation personnel, croakers, nurses, and the general public bear duty for disposing of PPE goods through proper channels in accordance with Central solution Control Board (CPCB) India) and biomedical waste management (BMWM).
c. Regular health scans/webbing of the general public and cases in counter blockade centers, immunization, and discarding of biomedical waste through appropriate treatment processes with minimal waste and reduced transmission of contagious illness. Introduction to the CPCB Mobile App for the COVID-19 trash operation.
d. While the risk of COVID-19 transmission through handling of a corpse is low, health care profess-sionals and anyone who handles corpses should use basic precautions at all times. A corpse confirmed or suspected to have COVID-19 should be wrapped in cloth or fabric and transferred to the mortuary area as soon as possible [95].
e. Healthcare professionals or morgue attendants must wear a mite suit, an impenetrable disposable gown (or a disposable gown with an impenetrable apron), face protection (rather) or goggles, gloves, a mask, and thrills when preparing the body. The PPE should be precisely taken off after use and decontaminated or discarded as contagious trash as soon as possible, and hand cleanliness should be performed.

In this pandemic situation of COVID-19, huge quantity of BMW generated and hence it is challenging to manage generated waste as this disease easily spread. Here, we have given some of the criteria's, one which helps to face these challenges of COVID-19 [50, 95].

Challenges related to HCWM are briefly discussed here and throughout this document. Sterilization of hazardous waste should be done to reduce transmission of the virus through incineration, energy-based treatment (radio wave, microwave) steam-sterilization (autoclaving), and chemical disinfection must be implemented [96]. High-temperature burn incineration has been recommended by WHO for treating infectious waste [97]. Deep burial should be practiced as an alternative to such technologies [26, 98]. To prevent contamination from waste, safe storage, collection, and transportation to a centralized treatment area should be implemented [26, 99]. Garbage collectors should have safety equipment in order to help curb the risks [100]. Health risks and safety of labor would be reduced by switching to system that are automated for separating waste. These introduced systems for separation may improve the effectiveness and speed of recycling thereby increasing value and quality of products [101]. Despite automated systems eliminating the necessity for handwork, there could be generation of employment by these improved waste valorizations in the fields linked with the useful implementation of the products. Thus, to curb the spread of COVID-19, waste management is a vital public service by safe handling and disposal of waste [102].

Countries demonstrating best practices in HCWM include Sweden, Switzerland, Denmark, Netherlands, Japan, US, Canada, Australia, Germany, and UK, with strengths in regulations, waste segregation, training, and innovative solutions. Emerging economies like China, India, Brazil, South Africa, and Indonesia are rapidly developing HCWM infrastructure and policies. However, COVID-19 highlighted global obstacles such as increased waste generation, inadequate PPE, lack of training, and insufficient infrastructure. Country-specific challenges include supply chain disruptions (US), limited infrastructure (India), inadequate segregation (Brazil), and insufficient regulations (Indonesia). To improve HCWM, countries should develop context-specific guidelines, enhance training, upgrade infrastructure, promote public awareness, foster international collaboration, and encourage innovative solutions.

Conclusions

COVID-19 waste management is very critical and should be managed promptly and effectively utilizing a proper plan, process, care, and precautions. The pandemic had and continues to have a negative effect on hospitals and their environments, on the health of the general population, communities, and nations, in general. For facilities that serve COVID-19 confirmed cases, regulatory adjustments in biological waste management have been implemented, requiring process changes to handle COVID-19 HCW. For handling of COVID-19 biomedical waste, process modification, proper training for collection, segregation, storage and transportation training are a prerequisite for effective COVID waste management. Responsive leadership coordinating with vigorous communication and training system will be helpful for time-to-time changes in structure and process for fruitful outcomes. Supporting nations who do not have the fiscal capacity to fund social policies, particularly universal social security programs, would require a coordinated global effort. Thus, COVID-19 pandemic created several innovations for health and environment with significant scientific contribution for several process development related to mitigation of environmental hazardous waste. As the pandemic continues, the amount of trash being generated becomes one of the most difficult tasks to manage. Timely improvements in structure and procedures for improved outcomes have been aided by responsive leadership working in harmony with a strong communication and training system. Present study on global HCWM during COVID - 19 has limitations, including reliance on existing literature, geographic bias towards high-income countries, and a focus on short-term implications. Data quality and availability issues, particularly from low- and middle-income countries, also constrain the analysis. Further research should investigate healthcare waste generation rates, composition, and management practices in diverse settings, develop predictive models, and evaluate the effectiveness of policy interventions. Exploring circular economy approaches, technology integration, and public-private partnerships can also enhance healthcare waste management. Longitudinal studies and primary data collection are necessary to address knowledge gaps and inform evidence-based policy decisions.

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