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Healthcare waste in Bangladesh: Current status, the impact of Covid-19 and sustainable management with life cycle and circular economy framework

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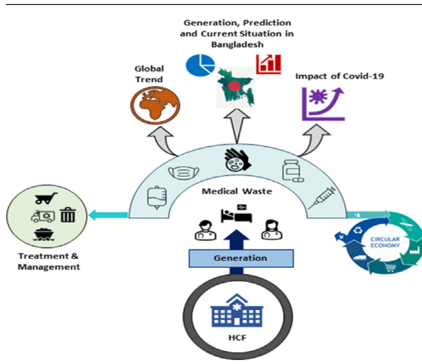
HIGHLIGHTS

- The existing medical waste (MW) management scenario of Bangladesh was reported.
- In 2025, the generation of 50,000 tons of MW was predicted using an empirical model.
- The excessive medical kits use accelerated the MW generation during the Covid-19 period.
- Limited implementation of legislation created poor MW management in Bangladesh.
- A sustainable circular economy model was proposed for MW management in Bangladesh.

GRAPHICAL ABSTRACT



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ABSTRACT

COVID-19 has accelerated the generation of healthcare (medical) waste throughout the world. Developing countries are the most affected by this hazardous and toxic medical waste due to poor management systems. In recent years, Bangladesh has experienced increasing medical waste generation with estimated growth of 3 % per year. The existing healthcare waste management in Bangladesh is far behind the sustainable waste management concept. To achieve an effective waste management structure, Bangladesh has to implement life cycle assessment (LCA) and circular economy (CE) concepts in this area. However, inadequate data and insufficient research in this field are the primary barriers to the establishment of an efficient medical waste management systen in Bangladesh. This study is introduced as a guidebook containing a comprehensive overview of the medical waste generation scenario, management techniques, Covid-

Abbreviations: DGHS, Director-General of Health Services; UNDP, United Nations Development Project; LE, Life expectancy; HDI, human development index; MW, medical waste; MWGR, Medical waste generation rate; GoB, Government of Bangladesh; DNCC, Dhaka North City Corporation; NGO, Non-government Organization; CE, Circular economy; MoEFCC, Ministry of Environment, Forestry and Climate Change; GW, Global warming; MWM, Medical waste management; HT, Human toxicity; TET, Terrestrial eco-toxicity; HCS, Health care services; HCFs, Health care facilities; HCW, Health care waste; HCWGR, Health care waste generation rate; WHO, World Health Organization; US EPA, United States Environmental Protection Agencies; EU, European Union; MoHFW, Ministry of Health and Family Welfare; DSCC, Dhaka South City Corporation; PPE, Personal Protective Equipment; SDG, Sustainable development goal; LCA, Life cycle assessment; LCIA, Life cycle impact assessment; FWAET, Freshwater aquatic eco-toxicity; CCC, Chittagong City Corporation; HCWMS, Health care waste management system; ETP, Effluent treatment plant.

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19 impact from treatment to testing and vaccination, and the circular economy concept for sustainable waste management in Bangladesh. The estimated generation of medical waste in Bangladesh without considering the surge due to Covid-19 and other unusual medical emergencies would be approximately 50,000 tons (1.25 kg/bed/day) in 2025, out of which 12,435 tons were predicted to be hazardous waste. However, our calculation estimated that a total of 82,553, 168.4, and 2300 tons of medical waste was generated only from handling of Covid patients, test kits, and vaccination from March 2021 to May 2022. Applicability of existing guidelines, and legislation to handle the current situation and feasibility of LCA on medical waste management system to minimize environmental impact were scrutinized. Incineration with energy recovery and microwave sterilization were found to be the best treatment techniques with minimal environmental impact. A circular economy model with the concept of waste minimizaton, and value recovery was proposed for sustainable medical waste management. This study suggests proper training on healthcare waste management, proposing strict regulations, structured research allocation, and implementation of public-private partnerships to reduce, and control medical waste generation for creating a sustainable medical waste management system in Bangladesh.

Contents

1. Introduction

Healthcare waste, associated with clinical activities during diagnosis, treatment, and research purposes of humans and animals, contains both hazardous (15 %) and non-hazardous wastes (85 %). (European Commission, 2000; US EPA, 2016; WHO, 2014). There are no definite concrete definitions of medical waste (MW) as it varies depending on the viewpoint and economic status of countries and regions (Windfeld and Brooks, 2015). In different literature, MW is also referred to as hospital/health care waste (HCW), or biomedical waste (BMW) (Minoglou et al., 2017). Some of the selected definitions of MW that are stated by WHO, US EPA, EU, and GoB are summarized in Table S1. MW in general is classified as non-hazardous or domestic waste and hazardous waste. Non-hazardous waste contains materials generated from administrative, housekeeping functions, and maintenance and mainly contains packaging plastic, food, and paper wastage (WHO, 2014). Hazardous waste is generally categorized into 7 groups e.g., sharp waste, infectious waste, pathological waste, pharmaceutical waste, cytotoxic waste, chemical waste, and radioactive waste (WHO, 2014; Zamparas et al., 2019). The definition and examples of each type of category are tabulated in Table S2. The MoEFCC, GoB classified the MW from class-1 to class-11 which are general waste, anatomical waste, pathological waste, chemical waste, pharmaceutical waste, contaminated waste, radioactive waste, sharp waste, general reusable waste, liquid waste and pressurized waste respectfully (DoE and GoB, 2008; JJS-IPEN, 2021; Khandaker et al., 2021; Naushad et al., 2019; Islam et al., 2020, 2023; Mazrouaa et al., 2019; Hasan et al., 2023a, 2023b; Rasel et al., 2023). It is tough to generalize and compare the composition and the medical waste generation (MWG) scenario as it varies depending on various socioeconomic parameters, different legal frameworks, average healthcare expenditure, lack of proper data, illegal dumping, etc. (Minoglou et al., 2017; Singh et al., 2022; WHO, 2004). Higher-income countries are prone to generate more medical waste (4–8.2 kg/bed/day) than lower-income countries (1–2 kg/bed/day). But higher-income countries also found to maintain the general guidelines and legislation imposed by local government and international bodies which is very unlikely for the lower-income countries (Mbongwe et al., 2008; Minoglou et al., 2017; Singh et al., 2022; WHO, 2014; Windfeld and Brooks, 2015). But recent literature pointed out the increase of the medical waste generation rate (MWGR) in developing countries with the improvement of economic status, availability of health care, and technological advancement (Korkut, 2018). Bangladesh, which is undergoing rapid economic growth in recent years, has also been found to follow increasing MW generation with estimated growth of 3 %

per year (MOHFW, 2011). It is very crucial to properly segregate, treat and dispose of the hazardous MW, however, WHO estimated that one out of three health care facilities (HCFs) lacks the safe management criteria (WHO, 2004, 2022a). Only 44 % HCFs of the developing countries from the South East Asian region were found to follow proper segregation, disposal, and treatment processes (Singh et al., 2022). Similarly, the health care waste management (HCWM) scenario in Bangladesh is found to be extremely poor due to limitations of existing legislation, inadequate training and infrastructure facilities, budget allocation, and negligence from both the government and the mass public (Barua and Hossain, 2021; Rahman et al., 2020b). Most of the studies conducted on HCWM found that the majority of HCFs didn't follow standard management procedures. Lack of adequate and reliable data, inadequate research, and unregulated scavenging and dumping of medical waste are also the reasons for the poor medical waste management (MWM) system in Bangladesh. (Dana, 2011; Noman, 2018; PRISM, 2022; Rahman et al., 2020b).

It is the occupational risks, occurring both inside (injuries, contamination) and outside of HCFs (Environmental risks i.e., air, water pollution, and possible transmission of diseases), that are leading the MWM system to be more critical (Cosimato and Vona, 2020; WHO, 2014). To reduce the risk associated with the MW, HCFs and the regulatory bodies follow different pathways but common routes are collection, color-coded segregation, storage, treatment, and disposal. Color-coded segregation, collection and incineration are the common practice in developing and poor countries including Bangladesh (Khan et al., 2019; Minoglou et al., 2017; Singh et al., 2022). Among different available thermal, chemical, irradiation, and biological treatment processes, autoclaving is turned out to be the best-suited process. Recycling and reusability of MW seem promising but they pose great difficulty due to the possibility of the spread of infection, degradation of quality, and ethical concerns (Cosimato and Vona, 2020; WHO, 2014).

The difficulty with MWM got even worse during the Covid-19 pandemic. The unprecedented rise in MWG is due to the excessive use of PPE, vaccination, and test kits (Al-Omran et al., 2021; Chowdhury et al., 2022; WHO, 2022a). In Asian countries, MWG increased 10 times than the normal times (WHO, 2022a). Bangladesh also saw a record rise in MWG increasing from an average of 1.6–1.99 kg/bed/day to 3.4 kg/bed/day (Barua and Hossain, 2021; Rahman et al., 2020b). MWGR varied with the infection rate and around 14,500 tons of MW had been produced just in April 2020 (Rahman et al., 2020a). Due to the limited capacity to handle MW in Bangladesh, most of the MW generated during this period was disposed of as untreated. A Study revealed that 93 % of covid-19 related MW was untreated and dumped with general municipal solid waste (MSW) in landfills or thrown in open spaces in Bangladesh (BRAC, 2020). Only 35 tons/day got properly treated among 248 tons/day that was produced throughout the country (BRAC, 2020). Another load of medical waste has been imposed by the countrywide mass vaccination. Vaccination procedures produce medical waste like vials, syringes, sharp materials, PPE, cotton with blood, etc. which are potentially infectious too. Already around 120 million 1st doses of vaccine have been administrated and this has created an extra pressure on the existing poor MWM system of Bangladesh (DGHS, 2022).

Sustainable waste management has become the main priority nowadays. For that, the current environmental impacts of existing HCWM system have to be compared with the reduction due to changing the strategies. To track the uses of resources and environmental effects i.e., GHG emissions, human, fresh water, and terrestrial toxicity due to MW, life cycle assessment (LCA) can be considered the best tool. This helps to choose the best suitable method for the MW treatment process considering a clearly defined system boundary, raw materials, and product streams (Ibáñez-Forés et al., 2021; Mehmeti et al., 2018; Muralikrishna and Manickam, 2017). There are very limited studies available on the LCA of MW worldwide and Bangladesh which is lacking in adopting a suitable method for MWM can take the advantage of LCA of MW for decision-making. Developed countries now not only consider the safe treatment process of MW but also are trying to attain sustainable routes for MWM (Masood et al., 2022; Marzana et al., 2022; Hayat et al., 2022; Akhoondi et al., 2022). Circular economy (CE) is the best technique to attain sustainability in MWM starting from reducing waste generation to reusing and recycling the possible materials. But the scope for implementing the CE concept in MWM is challenging due to the presence of hazardous materials (Brennan et al., 2015; Geissdoerfer et al., 2017; Morseletto, 2020; Sharma et al., 2021).

Inadequate data availability and lack of enough research in this field in Bangladesh, made this critical topic gain less attention from GoB, the media, and the mass people. Most of the studies, that are available, are scattered and lack proper research procedures. The recent studies that reported the effects of Covid-19 in the MWG scenario in Bangladesh cited the previous MWGR from the reports published before 2015. Moreover, these studies are based on the scenario of Dhaka only, excluding the other cities. The authors of this study tried to gather all the primary and secondary information available about MWG in Bangladesh to provide a spatial and temporal overview. To our best knowledge, there is no study currently available in the country which contains a full overview of the MWG scenario, management procedures, Covid-19 impact from treatment to testing and vaccination, and circular economy concept for sustainable MWM.

Thus, the current study is set to provide a brief overview of current MWG, compositional analysis of MW both worldwide and in Bangladesh. The prediction of MWGR in Bangladesh is provided and this was analyzed from a regression modeling by considering 4 socio-economic parameters. This study summarized the outcomes of different studies around the globe about the surges of MWG due to Covid-19. This study also contains our analysis of daily, and monthly production of HCW because of Covid-19 infection, tests conducted, and vaccination in Bangladesh up to June 2022. We have also incorporated a short overview of available international and country guidelines, rules, and legislation for handling MW and standard management processes as well as the current status of MWM existed in Bangladesh. Here, a medical wastewater treatment procedure is recommended with the existing scenario. The developed sustainable MWM model and the provided recommendations that are constructed here after going through the circular economy concept can help the stakeholders to rethink the existing scenario and to implement a more sustainable management system for the country. The authors believe this study can provide a complete analysis of MW in Bangladesh from the early days to the current post-Covid situation. This can lessen the difficulties a researcher or technologist may experience when doing a preliminary study in this field and we hope that this can create a base for more research and attention in this field in Bangladesh.

2. Methodology

2.1. Literature review and data sources

An extensive literature review was carried out to find the current status of medical waste generation, classification, and management practices followed globally and in Bangladesh. The keywords were ‘Medical Waste’, ‘Biomedical Waste’, ‘Health Care Waste’, ‘Types of Medical Waste’, ‘Medical Waste Management, ‘Medical Waste Treatment’, ‘Medical Waste in Bangladesh’, ‘Medical Waste during Covid-19’-were used for finding major and minor literature from well-known publishers e.g., Elsevier, Springers, PubMed, Wiley, Taylor Francies, etc. Reports from the WHO is also considered for the review process. For the life cycle analysis and circular economy, the same strategies were followed to review highly cited papers in these fields.

Daily Covid-19 confirmed cases, deceased patient numbers, monthly vaccination data, and monthly Covid-19 tests conducted from March 2020 to June 2022 taken from the Covid-19 Dashboard for Bangladesh of DGHS (DGHS, 2022). Worldwide confirmed cases and vaccination data were taken from Worldometer (Worldometer, 2022). Four socio-economic parameters of Bangladesh- Human development index (HDI), carbon emission per capita (CE, ton/capita), mean years of schooling (MYS), and life expectancy at birth (LE) from 2010 to 2019 are obtained from the data center of United Nation Development Program (UNDP) (UNDP, 2020).

2.2. Estimation of MWGR from the empirical model

A linear regression empirical model considering 4 socioeconomic parameters that affect the MWGR is developed by (Minoglou et al., 2017) taking data from 44 countries. The following best-fitted equations with the highest R^2 value were used for projecting MWGR in Bangladesh.

$$MWGR = 0.014 \times LE + 0.31 \times CE$$

$$MWGR = 1.5 \times HDI + 0.29 \times CE$$

$$MWGR = 0.13 \times MYS + 0.278 \times CE$$

Where MWGR = medical waste generation rate (kg/bed/day), LE = Life expectancy (years), CE = CO_2 emission (Tons/per capita/year) and HDI = Human Development Index, and MYS = mean years of schooling (years). Multiplication generated MWGR with the total number of beds available will give waste generation in tons/day.

2.3. Estimation of medical waste generation due to Covid-19 infection

MW generation due to Covid-19 infected patients was calculated as proposed by (Haque et al., 2021a; Mihai, 2020; Sangkham, 2020a).

$$W_m = \frac{N \times W_{gr}}{1000}$$

$$N = (N_i - N_d)$$

where, W_m is the medical waste generation (tons/day), W_{gr} is the generation rate (kg/bed/day), N is the number of patients, N_i is the number of the infected patient and N_d is the number of the deceased patient. W_{gr} depends on which country is under consideration but Covid-19 increased the hazardous waste generation rate to 3.4 kg/bed/day in Asian countries (IETC and UNEP, 2020). For this study, W_{gr} is taken at 3.4/kg/day. In Bangladesh, one Covid patient stays in HCFs for around 7–8 days (Barua and Hossain, 2021). For determining total waste production from one infected person in tons, W_m was multiplied by 7 days.

2.4. Estimation of MW generation from testing and vaccination

Vaccination and test kits for detecting Covid-19 produce infectious materials which are considered hazardous waste as they contain chemical reagent bottles or vials, alcohol swabs, nasal swabs, and syringes (WHO, 2022a). The total weight of these is taken from (Al-Omran et al., 2021; WHO, 2022a) and used for determining total waste generation using the following equations.

$$W_{test} = \frac{W_{test\ kit} \times N_{test}}{1000}$$

$$W_{vaccine} = \frac{W_{vaccine\ kit} \times N_{vaccine}}{1000}$$

where W_{test} and $W_{vaccine}$ are the amounts of waste generated in tons. N_{test} and $N_{vaccine}$ are the numbers of tests conducted and administrated vaccines respectfully. One vaccine produces around 8.24 g of waste and one conducted test generates 12.53 g of waste (Al-Omran et al., 2021; WHO, 2022a).

3. Medical waste: Generation and composition

3.1. Global perspective

HCW generation is generally expressed as kg/bed/day. The generation rate and the composition of HCW vary depending on several factors. These factors can be economic status (GDP, GNI), health care expenditure, rules, legislations and implementation, life expectancies of the people (LE), human development index (HDI) of a country, segregation method used, whether or not expressed as total MWG or only hazardous waste and most importantly location and which type of HCFs are chosen (Minoglou et al., 2017; WHO, 2014; Windfeld and Brooks, 2015). Higher-income countries are found to produce an average of 0.5 kg/bed/day of hazardous waste and poor and middle-income countries generate 0.2 kg/bed/day (WHO, 2022b). Fig. 1 shows that countries having higher HDI values generate higher medical waste. USA and Canada generate 8.4 and 8.2 kg/

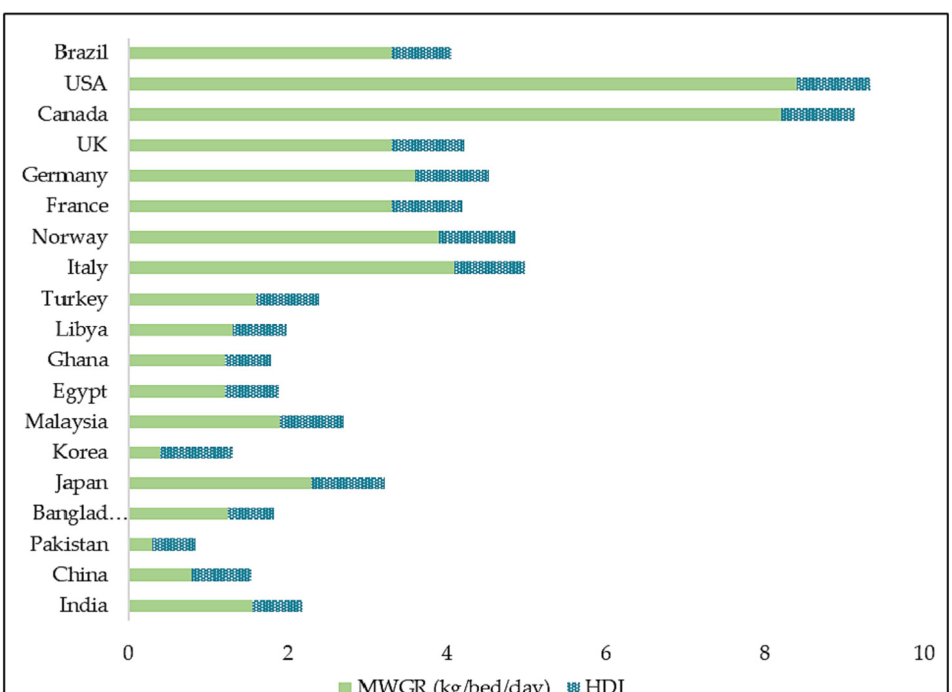

Fig. 1. HCW generation rate (kg/bed/day) and Human Development Index (HDI) of different countries of the world. HCW data are taken from (Ali et al., 2017; Minoglou et al., 2017; Singh et al., 2022) and HDI data are from the calendar year 2015(UNDP, 2022).

Table 1
Tabulated information regarding HCW and HCWM systems found in different studies carried out in the different regions of Bangladesh. Here, H = Hazardous waste; T = total medical waste; G = general non-hazardous medical waste.

Study region	The number or type of HCFs considered	Year	Key findings			Ref
			Waste generation		Composition, MWM system	
			Kg/bed/day	Ton/day		
Dhaka.	69 HCFs. 4 hospitals, 21 clinics and 44 diagnostic/ pathological centers.	2006	0.28 (H)	37 ± 5 (T)	21 % of the sample was found to contain hazardous substances which varied with the size and type of HCFs. Diagnostic centers were found to contain highly hazardous substances (48.4 %) whereas clinics and hospitals contain lower (22.5 %). Only 10 % HCFs were found to follow proper guidelines for disposal and treatment and 25 % follow a partial treatment process.	(Patwary et al., 2009)
Dhaka (DSCC)	1012 HCFs. Including 17 % hospitals, 16 % clinics, 21 % diagnostic centers and 46 % dental clinic.	2012	1.99 (T)	27 (T) 7.13 (H)	26.4 % of hazardous waste was found. Hospitals generated a higher amount of waste compared to non-residential labs, and diagnostic centers. Only 7 % of total HCFs managed their waste, 30 % follow partially and the remaining was disposed without proper management.	(PRISM, 2013)
DNCC			1.63 (T)	22.7 (T) 5.8 (H)	25.6 % of total medical waste contained hazardous waste. Only 12 % of HCFs managed their waste properly, 36 % managed partially and the rest of them didn't have a proper management system.	
Dhaka	5 HCFs. Containing both private and govt. hospital, clinics and pathological lab.	2016	2.6 (T)	5.6 (G) 1.5 (H)	20.6 % of hazardous waste was found. Of total waste 75 % general, 14 % infectious, 5 % plastic, 4 % liquid and 2 % sharp waste was found. Improper segregation procedure, dumping with MSW (70 % HCFs mixed with MSW) and extremely low awareness of medical waste was observed.	(Nuralam et al., 2017)
Dhaka (DNSC)	All the hospitals under DNSC.	2016	–	1.1 (T)	400 tons of MW was handled by Prism treatment facilities. Most of the hospitals didn't follow guidelines for the segregation process. Untreated MW is found on landfills, mixed with MSW bins and on streets and rooftops near the HCFs.	(DNCC, 2017)
Dhaka	50 private HCFs. Including hospital, clinic, dental and pathology labs.	2017	0.17 (H)	6.8 (H)	Waste generation rate varied with the type of HCFs selected and seasonal variation. 16.2 % was hazardous waste. Lower amount of waste produced in April and highest in June was found.	(Rumi and Karim, 2018)
Dhaka (DSCC)	30 HCFs. Including 4 public hospitals, 14 private hospitals, 4 clinics and 8 diagnostic centers.	2017	–	–	Of total waste 31.9 % general waste, 46.4 % pathological waste, 5.8 % sharp waste, 13 % chemical waste and 2,9 % chemical waste was found. 83 % of the hospital didn't have any segregation and treatment process.	(Mahiuddin and Hossain, 2017)
Dhaka	Five HCFs.	2017	–	200 (M)	77.45 % was a general waste, 14 % infectious waste, 3.8 % plastic waste 1.24 % and 3.4 % liquid waste and sharp waste was found.	(Mohiuddin, 2018)
Dhaka (DNSC)	486 HCFs. Including 2 % public hospitals, 21 % private hospitals, 21 % diagnostic centers, 45 % dental clinics.	2018	–	3.3 (T)	Of total waste, 75 % infectious, 15.7 % sharp, 11 % is recyclable waste was found.	(DNCC, 2019)
Rajshahi	6 HCFs containing 3 hospitals, 2 clinics and one pathological center.	2016	1.3 (G)	–	Hospitals generated higher amount of MW (1.17 kg/bed/day) than the clinics (0.13 kg/bed/day). The composition was found to vary with the type of HCFs. 54.37 % of total waste was infectious in a hospital. Color-coded segregation method was used but no proper handling, treatment process was used and no recycling process was utilized.	(Habib et al., 2016)
Jashore	One govt. hospital	2019	2.65 (T)	0.28 (T)	Around 8.5 % of total waste was MW which was found to vary with the seasons and type of wards. Emergency ward produced more MW than others.	(Haque et al., 2021b)
Rangpur	One govt. hospital	2019	1.00 (T)	0.35 (T)	19.4 % of the total waste was found to be medical waste. The delivery ward produces the highest amount of hazardous waste.	
Sylhet	17 HCFs having 3 public hospitals, 9 private hospitals and 6 clinics and diagnostic centers.	2003–2004	0.94 (T)	6 (T)	23 % was hazardous (15 % clinical and 8 % is sharp) and 73 % is non-hazardous (60 % general, 13 % reusable waste) waste. The generation rate was very low for diagnostic and pathological labs. Open dumping, mixed up with MSW and not enough facilities to handle and segregate MW was observed.	(Sarkar et al., 2006)
Khulna	23 HCFs containing private, public, diagnostic and clinics.	2014	0.78 (T)	0.24 (T)	12.5 % to 35.8 % of total waste was found to contain hazardous substances. MW was found to contain 4 % sharp, 5.2 % infectious and 6.2 % radioactive. Improper waste segregation and treatment were observed.	(Jeba and Rahman, 2020)
	20 HCFs including public, private and diagnostic centers having total 2073 beds.		0.90 (T) 0.18 (H)	0.58 (H)	Total HCW found to contain 80 % general, 8 % infectious, 5 % pathological, 4 % plastic, 2 % sharp and 1 % chemical waste. Public hospitals generated more HCW than the private hospitals and hazardous waste generated by the diagnostic centers found to be higher than rest of HCFs.	(Hasan and Rahman, 2018)
Jhenaidah	7 HCFs. Including both public and private hospitals and clinics.	2021	0.98 (T)	2.2 (T)	Of all waste generated in HCFs, 4.9 % was found to contain infectious, sharp, pathological and plastics substances. Only 46 % of generated MW is found to dispose of by municipal authorities and a NGO.	(Khan et al., 2021)
Noakhali	Total 109 HCFs. 72 was public and private hospital and the remaining is clinic and diagnostic centers.	2020	0.45 (T)	1.81 (T)	23 % of the total waste was hazardous (of which 47 % was infectious, 12 % pathological, 9 % sharp, 29 % pharmaceutical). A higher waste generation rate was found in hospitals. 80.7 % of HCFs didn't have any proper segregation method or standard treatment procedure, 17.4 % had partial treatment procedure and only 2 % have proper disposal procedures. MW was found to be disposed of with the MSW.	(Rahman et al., 2020b)
Whole Country	Total 9 hospitals of 9 district were chosen for the study.	2011	1 (T)	0.64 (T)	Total waste contained 79 % general waste, 8 % infectious, 3 % sharp and 10 % recyclable waste. Hospitals from Dhaka generated more medical waste (1.16 kg/bed/day) than others and the lowest ranges were found in less developed areas. 78 % of hospitals were found to mix with MSW and didn't have proper treatment or management facilities. Only 9 % HCFs found to follow the proper guidelines.	(Biswas et al., 2011)

bed/day respectively and Asian countries having moderate HDI produce comparatively lower medical waste (The maximum production rate is from Japan). European countries having almost the same higher HDI as North American countries, produces on average 3–4 kg/bed/day of medical waste. A study was conducted trying to co-relate various socioeconomic variables that can affect the HCW generation and found that HDI, LE, mean year of schooling, and CO_2 emissions have positive effects (Minoglou et al., 2017). These are the predictors of HCWGR for a country as higher values of those parameters indicate better healthcare services, better implementation of legislation, full utilizing most healthcare materials, and higher investment in healthcare services (Khan et al., 2019; Minoglou et al., 2017; Windfeld and Brooks, 2015). In recent days, developing countries are trying to provide better healthcare facilities to the mass community, and impose the strict implementation of the regulations. This is the reason for the increasing MWGR in developing countries. As an example, in Istanbul, Turkey, MWGR increased from 0.43 kg/bed/day in 2000 to 1.68 kg/bed/day in 2017 (Korkut, 2018).

85 % of total HCW is considered non-hazardous waste or general waste which contains plastic, papers, and food wastes produced from the maintenance of HCFs. Rest 15 % are hazardous substances which are categorized in Table S1 (WHO, 2014, 2022b). Around 15 % of MW is moisture and after combustion, 15 % of solid residue remains. Other general properties (Heating value, Bulk density) are tabulated in Table S3. Medical waste is highly heterogeneous containing plastic, paper (15–40 %), metal (1–10 %), glass (5–15 %), and fabrics (10–25 %). These values are useful in initial approximation as there are no benchmark values of HCW rather they can widely vary depending on the aforementioned factors (WHO, 2014).

3.2. Scenario in Bangladesh

Bangladesh currently has around 14,770 HCFs of which 654 public hospitals, 5055 private hospitals, and clinics along with 9061 diagnostic centers and pathological labs. A total of 141,903 beds are available for the patient which are producing a huge amount of MW throughout the country (Rahman et al., 2020a). There are several studies done for estimating HCWGR, characteristics of the waste generated (compositions, recyclable portion, hazardous content), and exiting management scenarios of the HCFs. Some of the selected studies are listed in Table 1 with important key findings. Although several studies are available for Bangladesh, the absence of standard procedures while conducting field surveys, improper data representation and expression (whether the generation rate is expressed as a hazardous portion or total waste), small sample size selection (considering only a few hospitals, not adequate sampling time, not enough waste collection) are observed in the studies which makes it difficult to generalize waste generation scenario for the whole country.

On average health care waste generation rate (HCWGR) is found to vary from 1 to 2.6 kg/bed/day throughout the country. Dhaka city is found to generate more medical waste than the rest of the regions although there is a lack of enough extensive studies in other divisions of the country compared to Dhaka. An extensive study was carried out taking into consideration of whole Dhaka city and this study estimated approximately 50 tons/day of medical waste generation of which 26 % was found to contain hazardous content (PRISM, 2013). A study was conducted solely on private HCFs in Dhaka by (Rumi and Karim, 2018) and found that private hospitals generate 0.17 kg/bed/day MW. In that study, the low patient admission to the highly specialized hospital due to cost was represented as the main reason behind lower waste production. Seasonal variability of waste generation is also found in the literature (Haque et al., 2021b; Rumi and Karim, 2018). High patient influx due to different seasonal outbreaks leads to higher MWG in the rainy seasons. The composition of MW is found to vary in every study. In general, hazardous waste is found to constitute 15 %–35 % of total MW. Composition and generation varied with the HCF type. In general, residential hospitals produced more MW than the pathological labs and diagnostics centers. The diagnostic centers mainly produce chemical (7 %) and infectious waste (13 %), whereas hospital mainly produces the bulk amount of non-hazardous waste (77 %) (Fig. 2, Fig. S1). Sharp waste remained between 4 %–6.5 % in every HCFs (Table S6).

In a study conducted by MoHFW, GoB projected the MWGR per year from 2009 to 2015 which was further extrapolated to 2025. This covered 6 divisional levels of the country considering 1.5 % population growth, 6.5 % of availability for health services with no significant change in demand in each year. The study found that medical waste generation will increase by approximately 3 % in each upcoming year. Dhaka was projected to produce 1930 tons/year of hazardous medical waste in 2025 and the lowest amount was predicted for Barishal (400 tons/year) as Barishal has fewer HCFs than Dhaka (MOHFW, 2011). Fig. 3 shows the trends in medical waste generation rates in the selected divisions. The total hazardous, general and total medical waste production rate from 2009 to 2025 is given in Fig. S2. This projection shows that country will produce a total of 50,000 tons of MW in 2025 where 12,435 tons is hazardous waste. Of course, the main limitation of this estimation is that it didn't consider the upgrading of the lifestyle and the improved health care system. The DNSC waste report of 2016–2017 stated that the city corporation authorities handled around 1350 tons of medical waste that year. This report also indicated that the MWGR is increasing per year with the increasing HCFs and enhancement of the ability for handling the MW (DNCC, 2017)

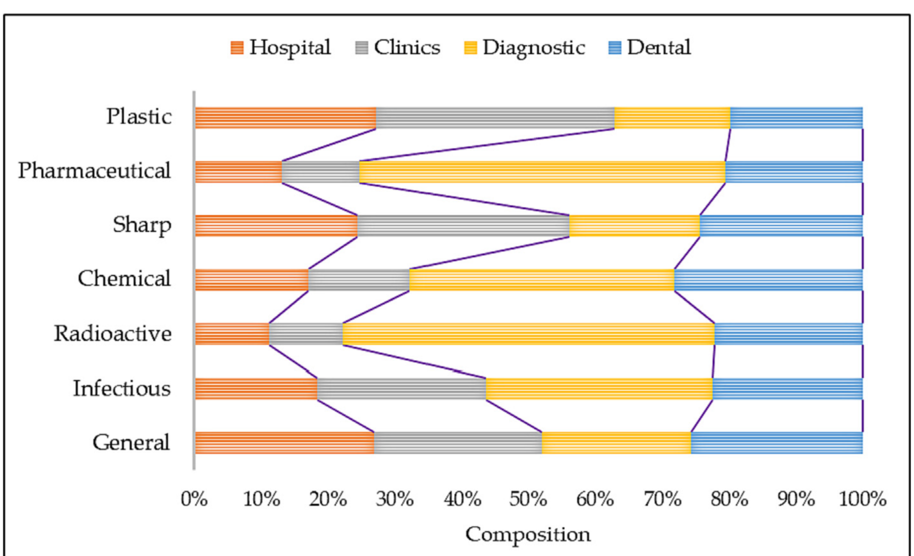

Fig. 2. Compositional analysis of medical waste collected from different HCFs. Data are taken from (PRISM, 2013).

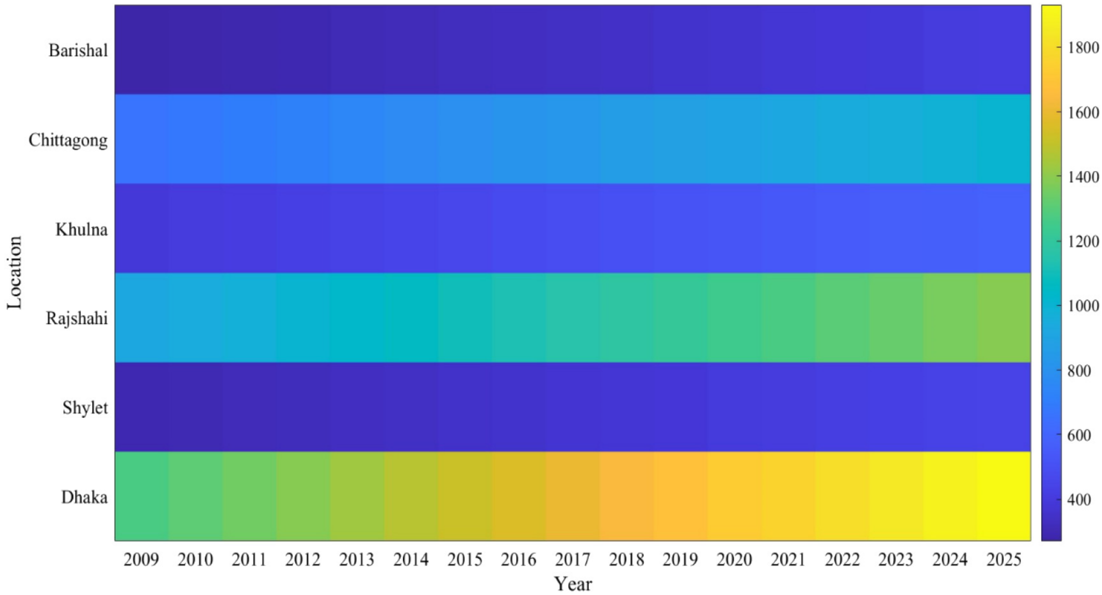

Fig. 3. Hazardous medical waste generation rate (Tons/year) of 6 divisions of Bangladesh. Values for 2016–2025 years are projected (MOHFW, 2011).

These studies were mainly conducted in the pre-covid-19 timeline, so they are more likely to depict the general medical waste generation and characteristics excluding the effect of major outbreaks.

3.2.1. Estimated MWG from empirical model

The socioeconomic parameters (HDI, CD, LE, and MYS) and the estimated MWGR are given in Table S5 using three empirical models (Section 2.2). The first model correlates the CO_2 emission (CD) and life expectancy at birth (LE) with MWGR. This model is highly statistically significant as developed by (Minoglou et al., 2017) and estimated higher MWGR than the rest of the two models (Table S5 and Fig. S3) but the predicted values from 2020 to 2025 for model-1 and model-2 are almost the same. MWGR is found to increase by about 9.6 % as Life expectancy (LE) and CD increased by approximately 3.85 % and 62.1 % respectively from 2010 to 2019 using model-1 (Fig. 4). The increase of LE and CD is directly related to medical waste generation as the higher the life expectancy and carbon emission, the better the health care system facilities of that country. These higher HCFs produce more MW. The generation rate is extrapolated up to 2025 which predicts that MWGR will increase to 1.25 kg/bed/day in 2025 which could lead to around 65,000 tons of medical waste generation in that year. From the study of MoHFW (MOHFW, 2011) around 50,000 tons were predicted which didn't take into account the effect of increasing HCFs and improving the healthcare system. Therefore, our model prediction is more suitable as this considers the overall economic status of the country. It is to be mentioned that this analysis is done assuming that stable economic growth of the country will prevail in the future and a stable increase in the healthcare system with the increasing living standard. Here surges of medical waste generation due to the Covid-19 situation are excluded and analyzed in Section 5.2 separately. So, the estimated values can be considered as the medical waste that will be generated from non-covid-19 related cases in the HCFs. This model prediction can be easily used in economic analysis of MW like circular economy analysis and decision-making procedures.

4. Effect of Covid-19 on medical waste generation

4.1. Overview of global scenario

An unprecedented situation has emerged due to the worldwide transmission of novel coronavirus (SARS-CoV-2) diseases, identified first in December 2019 in Wuhan, Hubei Province of China, which have affected almost every part of the world (Harapan et al., 2020). Up to July 2022, approximately 556 million confirmed cases has been reported and almost 6.4 million people have lost their life (Worldometer, 2022). To reduce community transmission every country imposed several restrictions measurements and implemented several guidelines for the healthcare personnel and general people including social distancing, wearing Personal Protective Equipment (Both surgical and nonmedical face masks, face shield, apron, gloves, and disposable coverings), frequently washing hands, etc. as per WHO recommendation. Along with the Covid-19 patient, billions of Covid-19 tests have been conducted and approximately 9 billion doses of vaccine have been administrated all over the world. The test kit and the vaccine contain a glass vial, swab, and syringes which are potentially infectious and considered as hazardous (Al-Omran et al., 2021; Chowdhury et al., 2022; WHO, 2022a).

Due to surges of Covid-19 patients and the use of excessive amounts of masks and PPE, medical waste generation increased enormously in every country which is potentially infectious (Sangkham, 2020b). According to an assessment led by UNDP in Asian cities, MWG increased 10 times due to Covid-19 than the previous, producing 3.4 kg/day/bed of hazardous MW (WHO, 2022a). Medical waste generation increased from 40 tons/day to 240 tons/day in Wuhan city whereas 469 tons/day MW was reported to be generated in China related to only Covid-19 (Sangkham, 2020b; Ye et al., 2022). In Malaysia, India, the Philippines, and Columbia 30 %, 17 %, 25 %, and 27 % increases in infectious waste generation in hospitals were recorded (Hantoko et al., 2021; WHO, 2022a) and in Indonesia, approximately 12,740 tons of MW were generated in 60 days after the first recorded Covid-19 case (Mihai, 2020).

Bangladesh first identified the Covid-19 case on 8 March 2020 (IEDCR, 2022) and up to July 6, 2022, approximately 2 million confirmed cases have been recorded of which around 29 thousand people have died. Around 14.42 million Covid-19 tests have been done throughout the country. From January 2021, 129.5 million people got their 1st dose of vaccine and 119.7 million and 29.8 million people are administrated with 2nd and a booster dose of vaccine (DGHS, 2022). Like other developing nations, Bangladesh also suffered from huge surges of MW due to the Covid-19 situation. Which lead to an increase in the MWG rate from an average of 1.6–1.99 kg/bed/day to 3.4 kg/bed/day (Barua and Hossain, 2021; Rahman et al., 2020b). MWG rate varies with the infection rate and around 14,500 tons of MW had been produced just in April 2020 (Rahman et al., 2020a).

4.2. Estimated Covid-19 related MWG in Bangladesh

Table 2 shows the total confirmed cases, deceased patients, total Covid-19 tests conducted, and vaccine administrated on monthly basis. Respective

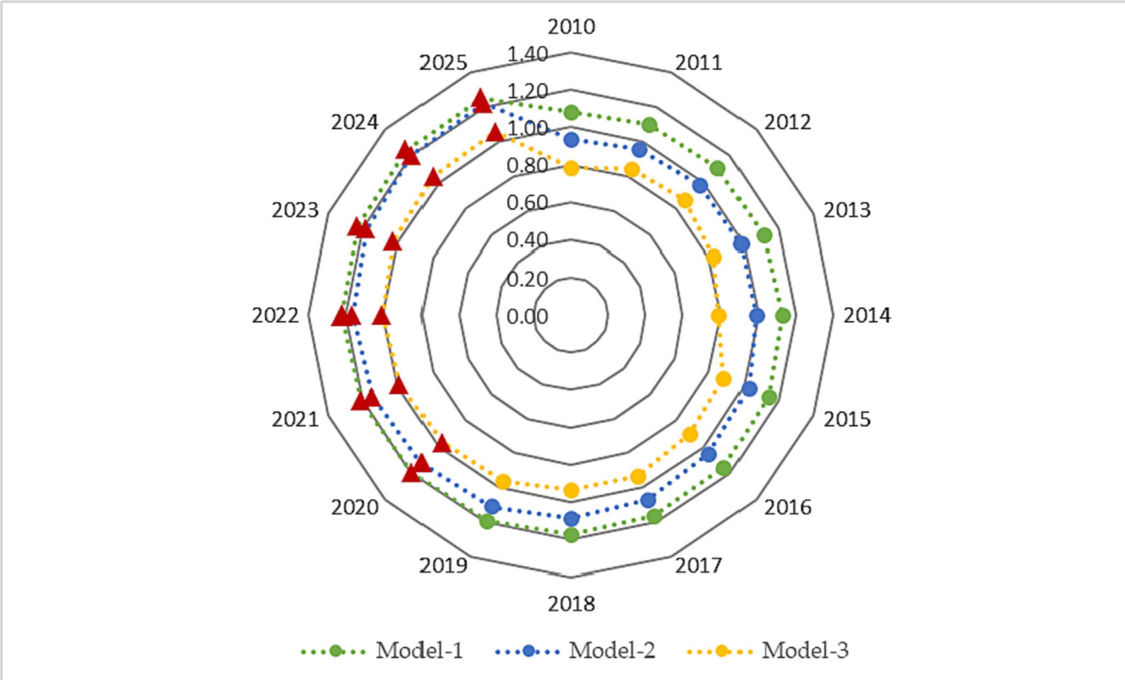

Fig. 4. Estimated medical waste generation rate (MWGR) in kg/bed/day using three empirical models which relate CE and LE. Red points denote the extrapolated values.

infectious waste generation from Covid-19-affected patients (Fig. 5), conducted tests, and vaccines are also tabulated in Table 2. In 2020, highest confirmed cases (98330) occurred in June and the infection rate decreased from September which can be considered as the end of 1st wave. Most of the Covid-19 related waste was generated from May to December in that year. A total of 11,643 tons of MW was produced in 2020. Bangladesh experienced the most severity of Covid infection in 2021. On July 2021, around 340,000 confirmed cases were recorded in a single month which is the highest till the present day. The 3rd wave of Covid-19 lasted 2 months, January 22 and February-22, although the death rate was lower than the 2nd wave (Table 2). Fig. 5 shows that with the increasing and decreasing of the infection, MWG also varied throughout the years. A total of 45,885

Table 2
Total number of confirmed COVID-19 cases, deceased patients, tests conducted along with medical waste generated from March 2020 to June 2022. Total number of vaccines administrated and medical waste generation from February 2021 to June 2022.

Time	Total number of				Medical waste generation		
	Confirmed cases	Deceased patient	Test	Vaccine	Patient (Ton)	Test (Ton)	Vaccine (Ton)
Mar-20	51	5	–	–	1.1	–	–
Apr-20	7618	163	–	–	177.4	–	–
May-20	39,486	482	–	–	928.3	–	–
Jun-20	98,330	1133	–	–	2313.3	–	–
Jul-20	75,244	1114	330,747	–	1764.3	4.1	–
Aug-20	75,335	1170	373,394	–	1765.1	4.7	–
Sep-20	50,483	970	397,452	–	1178.4	5.0	–
Oct-20	44,205	672	388,607	–	1036.1	4.9	–
Nov-20	57,248	721	436,439	–	1345.3	5.5	–
Dec-20	48,578	915	454,897	–	1134.4	5.7	–
Jan-21	21,629	568	424,124	–	501.3	5.3	–
Feb-21	11,077	281	392,305	3,109,958	256.9	4.9	25.6
Mar-21	65,079	638	626,549	2,259,906	1533.7	7.8	18.6
Apr-21	147,837	2404	799,627	3,254,919	3461.3	10.0	26.8
May-21	41,408	1169	477,809	1,370,737	957.7	6.0	11.3
Jun-21	112,718	1884	661,414	176,180	2637.8	8.3	1.5
Jul-21	336,226	6182	1,131,967	2,972,594	7855.0	14.1	24.5
Aug-21	251,134	5510	1,187,451	13,389,750	5845.9	14.8	110.3
Sep-21	55,293	1315	802,946	23,710,644	1284.7	10.0	195.4
Oct-21	13,628	358	618,579	21,147,456	315.8	7.7	174.3
Nov-21	6745	113	538,881	27,302,848	157.8	6.7	225.0
Dec-21	9255	91	602,757	26,934,602	218.1	7.5	221.9
Jan-22	213,294	322	987,194	35,842,333	5068.7	12.3	295.3
Feb-22	144,744	643	922,657	50,915,660	3429.6	11.5	419.5
Mar-22	8000	85	422,668	37,111,909	188.4	5.3	305.8
Apr-22	1114	5	166,459	8,293,201	26.4	2.1	68.3
May-22	816	4	134,756	3,914,554	19.3	1.7	32.3
Jun-22	20,278	18	225,463	16,509,481	482.2	2.8	136.0

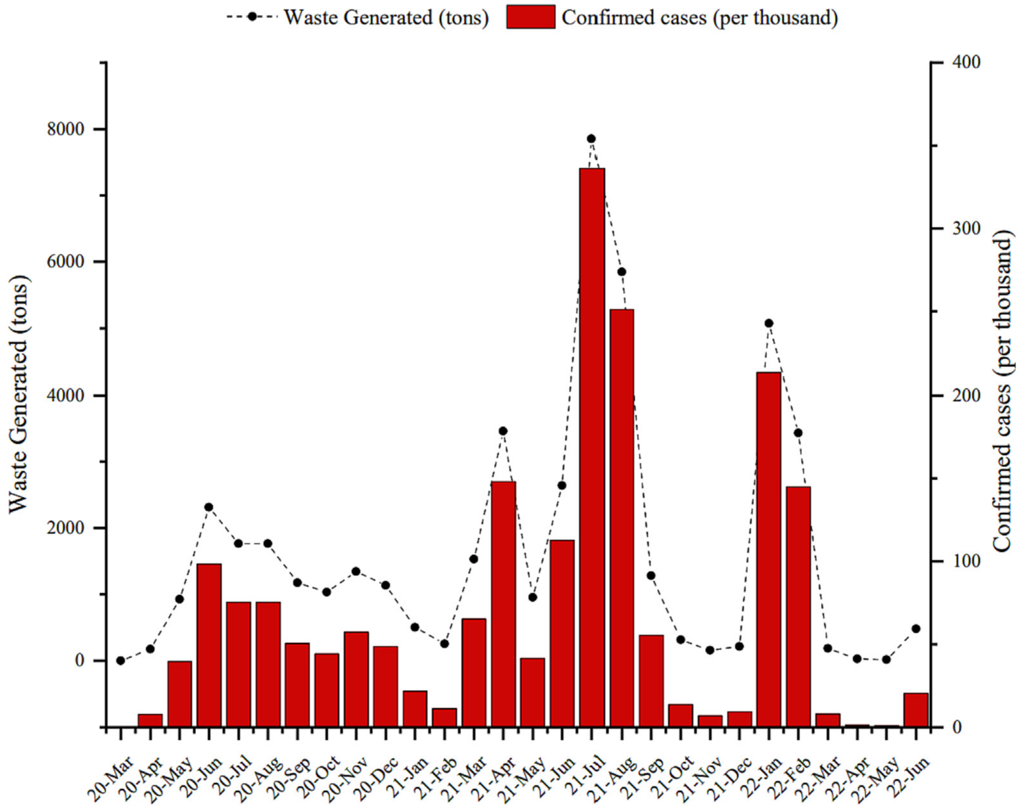

Fig. 5. Monthly medical waste generation in tons due to infection from March 2020 to July 2022.

tons of MW were generated from March 2020 to July 2022 considering Covid-19-related patients were treated on average for 7 days. Chowdhury et al. (2022) also estimated the MW generation from March 2020 to May 2021 (Chowdhury et al., 2022). He also found a similar trend in MWG due to hospital administration and rise of the infection rate. However, he has not considered the average hospital staying days of an infected person and multiplied the waste generated by an infected person by the days of the month. Thus, his estimation is way too large compared to ours.

The testing capacity of Bangladesh was low in the initial days which rapidly raised and almost 1.2 million tests were done on August-21. MW related to testing kits contributed a lower portion of the total MW generated during this period, 2–5 tons per month in normal conditions and 10–15 tons in peak times. A total of 168.4 tons of waste have been produced due to Covid-19 testing kits (Table 2). Vaccine administration in Bangladesh started on 27th January 2021. Initially, there was a holdback in mass vaccination as GoB could only manage vaccines from AstraZeneca on a limited scale. But GoB secured contracts and received vaccines from other sources like COVAX, Sinovac, Sinopharm and from friendly nations like India, China, USA and EU. Thus, due to mass vaccination, vaccine-related MW generation started to increase, producing 110 tons on August 21 to 420 tons on February 22. A total of 2300 tons of waste have been generated due to vaccine administration from February 2021 to July 2020. Chowdhury et al. (2022) estimated 188 tons of vaccine-related MWG from January 21 to August 2021 which is similar to our estimation. But they didn't conduct monthly variation of the vaccine related MWG (Chowdhury et al., 2022). In 2020, a survey led by ESDO (ESDO, 2020) found that 386 tons/day of potentially hazardous and non-hazardous plastic waste was generated of which 53 tons/day were from the single-use surgical masks that were disposed of every day (Fig. S4).

This part of the study gives a quick estimation for quantifying the amount of Covid-19-related MW generated during the study period. The result largely depends on the reliability of data and the accuracy of the taken assumptions. The real Covid-19 patient number is hard to identify as many people didn'*t*-test or admit into HCFs for treatment which is a common phenomenon in a developing country like Bangladesh. Moreover, the isolated persons and the persons who took home treatment is not considered here as data for those type of cases are unavailable to this extent. More research is needed on the actual waste generation rate from Covid-19 wards of HCFs, and waste generation from quarantined persons.

5. Guidelines, policies, and legislations

With the rapid population and economic growth, proper medical service demand led to an increase in MWG. Thus the concern about proper handling and disposal of MW has become a complex and demanding challenge and this requires definite guidelines, policies, and rules to control and maintain environmental pollution and public health (Mbongwe et al., 2008; Minoglou et al., 2017; Windfeld and Brooks, 2015). Up to days many international and regional conventions have been taken for safer handling and proper disposal of MW. Bessel Convention is one of the most comprehensive global environmental treaties that made the parties control the MW from generation to final disposal and prevention to transboundary movement from the place of generation (WHO, 2014). WHO has specific guidelines and recommendations for countries as well as for the NGOs, stakeholders, and private sectors to check the health care situation and for taking required policies and legislations for medical waste management (MWM). WHO recommends short, medium, and long-term strategies for MWM outlined in Table S-3 (WHO, 2004). International Solid Waste Association (ISWA), a non-profit international organization, supports and advocates for its members for the sustainable handling and management of healthcare waste (ISWA, 2022). Various studies have found that developed countries are more concerned about MW and have specific acts and proper, strict and regular implementation whereas the opposite scenario is observed in developing countries (Khan et al., 2019; Minoglou et al., 2017; Singh et al., 2022; Windfeld and Brooks, 2015).

United States Congress passed Medical Waste Tracking Act (MWTA) in 1988 which is used ever since in the USA and established a definition, classification, management standards, record keeping, and penalties if mismanaged (CSG, 1992; US EPA, 1988). The member nations of the European Union are responsible for following and setting legislation according to the directive (94/904/EC) set by European Commission (EC) (European Commission, 1994). Medical waste is included in chapter 18 of the European Waste Catalogue (EWC) with its different components and the EU countries developed their acts fulfilling the directives (Bertram et al., 2002; Windfeld and Brooks, 2015). India regulates the MW by Bio-Medical Waste (Management and Handling) Rules passed in 1998 (Khan et al., 2019).

Traditionally all types of wastes from HCFs were collected with the general wastes and then dumped and treated as per the municipal solid management system in Bangladesh. But with the increasing medical waste generation rate, GoB promulgated the Medical Waste (Management and Processing) Rules in 2008 which overcame the shortcomings of ECA, 1995 [25, 26]. Several other guidelines and policies have been taken and implemented by GoB under the authorization of DoE and DGHS where some of which are supported by UNDP and UNICEF (MOHFW and GoB, 2018). A brief overview of some of the major legislations, guidelines, and policies is given in Table 3.

Due to unprecedented surges of medical waste during the COVID-19 pandemic, existing plans were required to be updated with the formulation of several new guidelines and provisions (Barua and Hossain, 2021). DGHS and NIPSOM set the 'Guideline or Standards Operating Procedures (SOP) for Coronavirus Related Waste Management in Hospitals' in March 2020 containing the rules that the HCFs should follow to minimize environmental risk and infection risk caused by coronavirus-related wastes (DGHS and NIPSOM, 2020) For the safety of healthcare personnel and workers related to MWM, DGHS with the support from IEDCR'B, UNICEF, and WHO, formulated 'Rational Use of Personal Protective Equipment (PPE) for Covid-19' which also referred to MWM related to coronavirus (DGHS, 2020). Furthermore, DoE published a notice under ECA-1995 for the regulation of environmental pollution and prevention of coronavirus related to the medical waste disposed of HCFs. This also suggested using Covid-19 leveled two-layer color-coded sustainable bags and bins for the collection, and segregation of MW (Barua and Hossain, 2021).

6. Medical waste management

6.1. An overview of the MWM system

Medical waste is the result of medical, surgical, and treatment procedures conducted in healthcare facilities (Conrardy et al., 2010; Taghipour and Mosaferi, 2009). This waste must be handled and managed properly and WHO has provided general guidelines for the safer management of MW (Fig. S5). These guidelines ensure environmental protection, reduce the risks of human infection, the spread of infections, and the emergence of epidemics or pandemic such as Covid-19 (Woolridge and Hoboy, 2019). These also help to find a better way to manage MW. Moreover, the MWM hierarchy, a conceptual structure, helps to guide and prioritize optimized waste management actions at both the individual and organizational levels (Fig. S6) (Adu et al., 2020; Price and Joseph, 2000). Both hazardous and non-hazardous MW affect environmental health and quality of life; thus, appropriate MW management is critical in lowering the environmental and public health risks (Askarian et al., 2004; Rumi and Karim, 2018; Voudrias, 2016). In impoverished nations like Bangladesh, inappropriate treatment of MW can negatively impact the hospital environment and the population (Sarker et al., 2014).

Different countries have different waste management systems, but they all have the same fundamental steps: segregation, collection, storage, transportation, treatment, and disposal (Abdulla et al., 2008; Klangsin and Harding, 1998; WHO, 2014). How these steps work can be found in Table S6. There are several methods for treating medical waste which can be grouped into five major processes (WHO, 2014). Table S9 has summarized the description, relative advantages and disadvantages of the available treatment processes. The proper treatment process is to be selected after considering the waste characteristics, technological requirements, environmental and safety factors, cost of operation, capacity of the treatment system, etc. In Fig. S7, the factors that are to be considered for choosing an effective treatment process are depicted.

6.2. Medical waste management scenarios in Bangladesh

Although many guidelines and legislations are available, MWM still lacks effectiveness, and safety issues in Bangladesh which are also found to be common in other countries with transitional economies. Also, in developing countries, people involved in the collection of MW are reported to lack proper knowledge, training, and awareness, as well as they face injuries from handling sharp materials (Ali et al., 2017; Singh et al., 2022). Studies that were conducted across the Bangladesh about MWM scenario found that most of the HCFs didn't follow the color-coded segregation method suggested by DGHS and WHO. Open dumping and mixing up with the waste bin for MSW are found to be common phenomena. All of the HCFs didn't have any personal treatment facilities and they depend on a few NGOs who take care of MW i.e., PRISM, Swapno, Protidin, BASA, etc. The key outcomes from several studies conducted on Bangladesh about MWM are listed in Table 1. In Bangladesh, MW is mainly managed

Table 3
Brief description of available rules, legislations and policies undertaken by GoB with year of implementation and responsible authorities.

Act/polices	Year	Regulatory authorities	Description
Bangladesh Environmental Conservation Act (ECA) (MoEFCC, 1995)	1995	DoE	ECA is the main law relating the environmental protection in Bangladesh. This framework includes conservation and improvement of environmental standards, prevention, and mitigation of pollution.
Manual for Hospital Waste Management (DOHS, 2010)	2001 later updated on 2010	DGHS	These initial guidelines were used for ensuring the efficient and economical disposal of MW by creating a minimum environmental hazard.
Medical Waste (Management and Processing) Rules (DoE and GoB, 2008)	2008	DoE	Complete guidelines and rules for proper collection, management, transportation, treatment and disposal of MW are established by this law. These rules gives the classification, color-coded bins for segregation at source, appropriate symbols for packaging, guidelines for autoclaving, microwaving, incineration, standard for liquid waste and deep burial as well giving authorization to specific bodies and specific punishment rules if violated. This law gives the authorization to DoE to implement the rules and give licenses to other organizations that aim to work in MWM.
Guidelines for Infection Prevention and Control (IPC) and Biosafety (QIS MoHFW, 2018)	2016	DGHS	These guidelines focus on ensuring the safety of patients and healthcare personnel which are supported by WHO, Bangladesh to fulfill the WHO standard.
National Strategies for WASH in HCFs 2019–2023, A Framework for Action (MOHFW, 2019)	2019	DGHS	Funded by UNICEF to update the existing rules and regulations related to MWM, fulfilling international standards, arrangement of training and develop a proper organization for sustainable MWM.
Hazardous Waste Management Rules (DoE and GoB, 2021)	2021	DoE	This incorporated the rules for the treatment, collection, recycling, composting and associated penalties for illegally handling both E waste and hazardous medical waste produced in hospitals, manufacturing and household.

through NGOs that have a partnership with Govt. and they get support from some international organizations for the safe disposal of generated MW. PRISM Bangladesh, an NGO that started its operation in 1989 with the help of UN organizations, now collects MW from 1121 HCFs in Dhaka city. PRISM has only fully developed MWM procedure, treatment facilities, and disposal system in Bangladesh. This NGO engaged in the MWM system in 2004 in Dhaka and has currently expanded its operation to other major districts of Bangladesh (PRISM, 2022). From the points of generation, 56 % of clinical MW are disposed of in municipal waste, with the remaining 44 % managed by PRISM Bangladesh [3, 8]. Prism collects three types of MW (infectious, plastic, and sharp), and after final management, these MW are treated according to their type. Infectious wastes are treated through autoclaving, incineration, and burial method, sharp waste through autoclaving and deep burial, and plastic waste through chemical disinfection, shredding, and recycling (Fig. 6). Infectious wastes are sterilized in an autoclave at 135–140°C and 3 atm pressure for 45 min. At last, these treated MW are disposed into landfill sites. The highly infectious wastes are treated in two chamber incinerators. The minimum operating temperature for the first and second chambers are 850°C and 1050°C respectively. The ash formed in incineration and body parts from operation theaters is finally disposed of by concrete deep burial method. Concrete tanks, specially constructed to prevent soil and water pollution, are used to manage sharp wastes after adding chemicals. Plastic wastes are disinfected with NaOCl and Cl_2 and then recycled. Three types of tanks are used in this treatment process. In the 1st chlorination tank, plastic wastes are submerged for 45 min then these partially treated wastes are again submerged into the second chlorination tank for 20 min for the final chemical disinfection process. After that, in 3rd tank these wastes are washed with clean water and dried in sunlight and at last, by a mechanical shredder machine, they are recycled by cutting down into small pieces (PRISM, 2022).

A survey conducted in Dhaka City by PRISM in 2014 reported that on average 57 % HCFs collected MW without any management whereas 10 % HCFs followed color-coded segregation method and the rest of the HCFs found to follow partial segregation procedures (PRISM, 2013). This also varied depending on the type of HCFs. It was found that higher fractions of clinics and dental facilities manage MW properly compared to hospitals and pathologies (Fig. S8). Patwary et al. (2009) found in 2009 that the 68 % of the total HCFs didn't follow any segregation whereas only 7 % did follow proper collection procedures. This scenario is improved due to the increasing capacity of NGOs and also due to increasing training from DGHS. This situation was found to be further improved in a study conducted on 2017. This study found that 45 % of the HCFs had proper segregation and 72 % were found to use color-coded bins (Nuralam et al., 2017). The private HCFs in Dhaka were found to cooperate with PRISM and some were found to have open incineration and deep burial for disposal (Barua and Hossain, 2021; Rumi and Karim, 2018). During Covid-19, huge surges of MWG both in HCFs and household activities led the existing facilities to soar. A survey pointed out that 93 % of Covid-19 related MW were out of management. Only 35 tons/day got properly treated among produced 248 tons/day throughout the country. This study also found that 100 tons

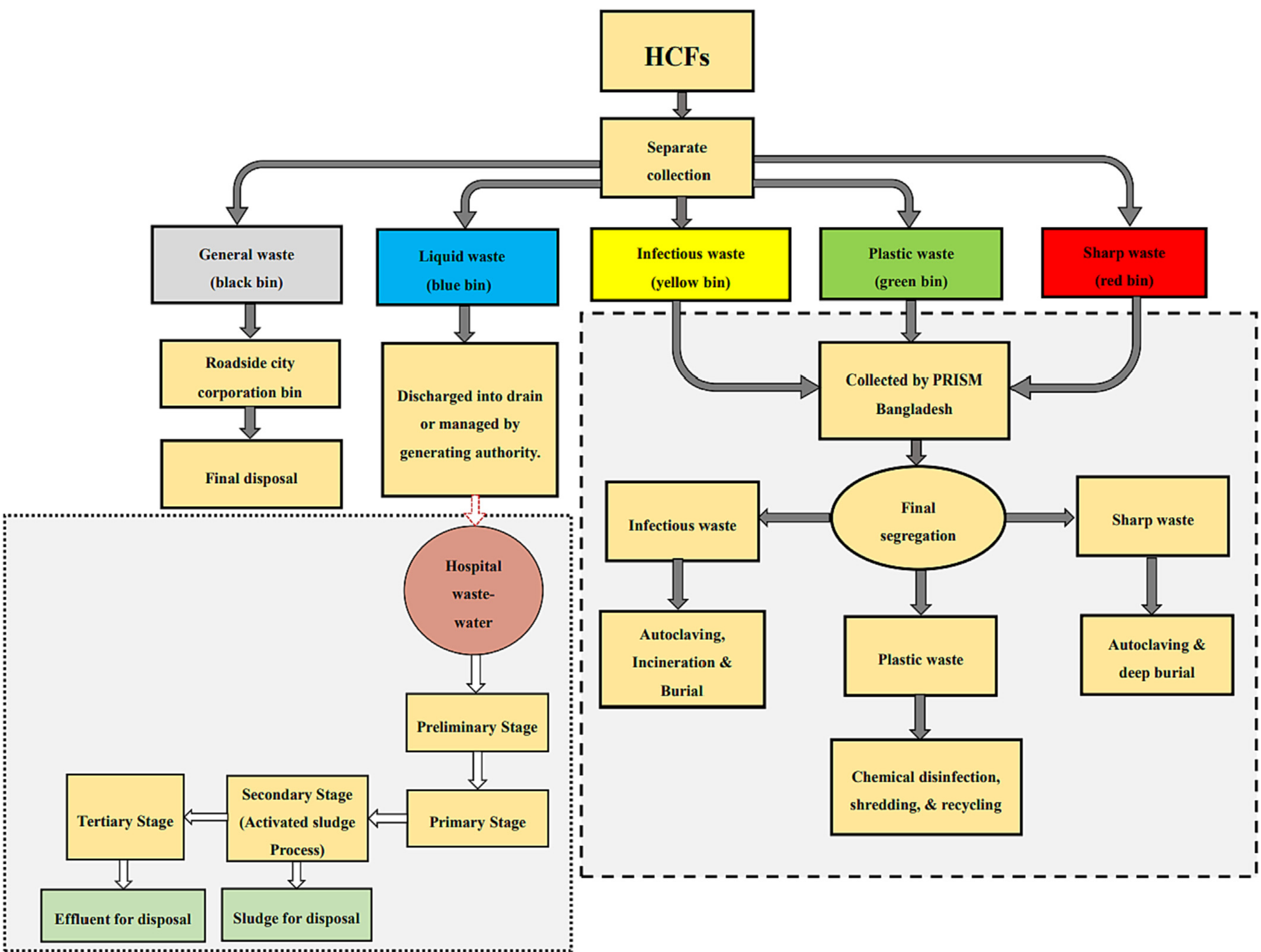

Fig. 6. PRISM approach of clinical waste management (– box indicates activities by PRISM Bangladesh & … box suggested standard hospital wastewater management procedure (Dana, 2011)).

of Covid-19-related MW produced from households ended in the MSW bins (BRAC, 2020). Existing literature found MW in open places, piled up backward of HCFs, streets, MSW dumping sites, canals and drains during Covid-19 (Barua and Hossain, 2021). Lack of implementation of legislation, unconcerned regulatory authorities, corruption, unconsciousness of the HCFs' stuff and cleaners, lack of proper training, absence of any CE strategies, gaps in existing rules and legislations, and economic constraints led to the improper MWM in Bangladesh (Barua and Hossain, 2021; Dana, 2011).

Hospital wastewater is crucial as it can spread viruses and other pathogens if disposed of without proper treatment (Gormley et al., 2020). Studies conducted during the recent Covid-19 outbreak discovered evidence of SARS-Cov-2 ribonucleic acid (RNA) in samples taken from wastewater treatment facilities (Mandal et al., 2020). Unfortunately, most HCFs in Bangladesh are ill-equipped to deal with wastewater. To effectively combat pandemics like Covid-19, a robust and well-thought-out strategy must be put into place. The enclosed area by the dot pattern in the Fig. 6 is a standard procedure that is effective for handling hospital or sewage wastewater (Alahdal et al., 2021; Wang et al., 2020). This model can be incorporated in Bangladesh too. At the pretreatment stage, inorganic solids and large-heavy debris are isolated to safeguard subsequent machinery and boost its efficiency. At the primary clarifier or primary solid filter, the particulates from the liquid get separated. This partially cleaned water then undergoes a secondary biological process where microorganisms are used to remove dissolved inorganic contaminants. At this point, the solid sludge is disposed of, and the effluent stream proceeds to the tertiary stage. A tertiary filter gets rid of the remaining suspended solids. Finally, the liquid stream undergoes a chemical (disinfection by ClO_2, NaOCl, H_2O_2, peracetic acid, lime solution, O_3, dry CaO powder, etc.), physical (UV, irradiation, etc.), or a combination of the two disinfection processes. In Table S9 details of the benefits and drawbacks of different methods are summarized (Akruthi Enviro Solutions Pvt. Ltd., 2022; Ilyas et al., 2020).

In Bangladesh, the importance of providing proper protective measures for the people who works in MWM is not given the attention it deserves. With the applied MWM process, we must also ensure the safety of those who work in the wastewater treatment units. Avoiding skin contact, ingestion, and inhalation of water mist, and wearing PPE are just some of the measures that wastewater treatment plant workers should follow (Barcelo, 2020).

7. Life cycle assessment

Life cycle assessment (LCA) is a methodology and an analysis tool used to examine the environmental implications of all stages of a product's life, from raw material extraction to materials processing, manufacturing, distribution, and consumption (Ibáñez-Forés et al., 2021; Muralikrishna and Manickam, 2017). LCA includes the use of fossil and mineral resources, land use, and emissions to the atmosphere, water, and soil (Mehmeti et al., 2018). Furthermore, the LCA findings can be utilized to identify important procedures that can be adjusted to reduce the overall environmental impact (Verma and Kumar, 2015). The LCA framework contains four distinct phases (Fig. 7): goal and scope definition, inventory analysis, impact assessment, and interpretation (ISO, 2020).

Goal and scope definition is the first and crucial step (Curran, 2017) for performing the LCA of HCMW. System boundary which is the indication of products of interest and its surrounding is needed to be clearly defined first (Li et al., 2014). The system boundary is divided mainly into three categories: the boundary between product and environment system, the boundary between significant and insignificant product system, and the boundary between considered and other product system (Curran, 2017; Li et al., 2014). After that life cycle inventory (LCI) which is nothing but inputs and outputs (both materials and energy) of the LCA model is to be constructed. In the LCI, all inputs and outputs associated with the management of HCMW are to be listed (Crawford et al., 2018). To find out the potential damages to health or the environment, the life cycle impact assessment (LCIA) has to be done (Pizzol et al., 2011). According to ISO standards, the last but most important phase is the interpretation of the LCA, which should identify key concerns, evaluate the LCA, and provide conclusions, limitations, and recommendations (Hans Bruijn et al., 2002).

LCA studies for achieving eco-friendly MWM system are rare worldwide and it is still ignored in Bangladesh. Very few studies are available that took the whole MWM system as the boundary condition. Zhao et al. (2021) conducted a comparative LCA on two scenarios (hazardous incineration and landfilling) with 5 alternatives (0, 15, and 30 % energy recovery in incineration and 0 and 10 % efficiency in landfilling) (Zhao et al., 2021). He found that the incineration procedure with 30 % energy recovery had the lowest impact. Dioxin emission contributed 10 % of human toxicity whereas landfilling process with and without energy recovery had seven times higher environmental effects than the incineration techniques. Soares et al. (2013) took autoclaving, microwaving, and lime disinfection as three different disinfection technologies for HCW disinfection for doing LCA and cost analysis (Soares et al., 2013). After the analysis, microwaving was found to have lower environmental impacts compared to the other two and also had a lower cost associated per kg of waste treated.

Since the start of the Covid-19 pandemic, a massive amount of medical waste has been generated, which is 145 times the typical rate, and the volumetric waste generation of high-income countries is nearly 5 times that of low-income countries (Liang et al., 2021; Parida et al., 2022). The life cycle assessment (LCA) is also a more trustworthy method for determining the most environmentally friendly technique for long-term MWM which can also satisfactorily operate during emergencies like Covid-19. Nabavi-Pelesaraei et al. (2022) conducted a thorough LCA analysis to determine the most environment-friendly procedure for dealing with emergencies (Nabavi-Pelesaraei et al., 2022). This study compared five disposal scenarios (incineration disposal vehicle, steam sterilization cabin, movable microwave sterilization equipment, co-incineration with hazardous waste, and co-incineration with municipal solid waste) among which three were mobile and two were co-incinerator processes. The detailed analysis was done using the ReCiPe2016 technique, which considered three parameters (human health, ecosystem, and resources) to evaluate environmental damages. The movable microwave sterilization equipment disposal scenario was found to have the least negative impact on the environment compared

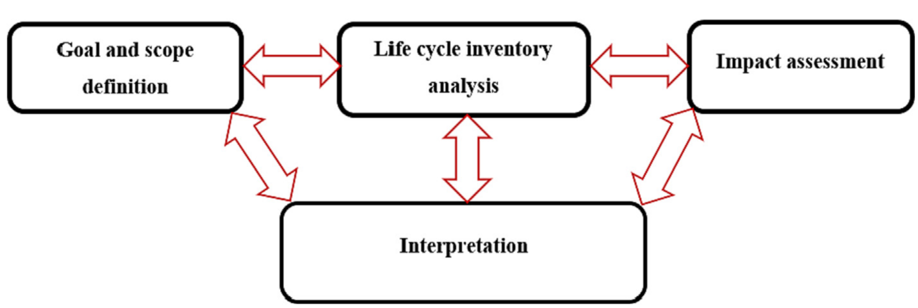

Fig. 7. Life Cycle Assessment (LCA) framework (Nabavi-Pelesaraei et al., 2022).

to the other scenarios, and the co-incineration with the municipal solid waste disposal scenario had the greatest negative impact.

One study conducted in Chittagong, Bangladesh took the whole HCWM system partially in the system boundary and compared three current management scenarios with a standard management scenario (Alam and Mosharraf, 2020). The current scenarios include temporal storage of medical waste, partial segregation, open burning, unlawful disposal, mixing with MSW bins, landfilling, and unlicensed recycling. These are very common practices throughout Bangladesh as discussed in Section 6. The fourth scenario included proper segregation and recycling process as well as standard treatment procedures like steam sterilization, autoclaving, incineration with energy recovery, and restricted disposal. Fig. 8 summarizes the principal findings of the study. Open burning, unlawful disposal, and open dumping mainly contributed to global warming (CW), human toxicity (HT), freshwater aquatic eco-toxicity (FWAET), and terrestrial eco-toxicity (TET). Although that study was incomplete, it clearly showed the lower environmental impacts of the MWM scenario that included standard collection, treatment, recycling, and incineration with energy recovery. These discussed studies can indicate the proper technologies that can be chosen prior to installing an eco-friendly MWM system in Bangladesh. LCA result and interpretation may vary if the system boundary, composition of MW, location, and input-emission definition change. Because there are no substantial studies on the LCA of MWM in Bangladesh, there is an excellent opportunity for researchers to seize and propose suitable health and environmentally friendly MWM system.

8. Circular economy: Current status, scopes and recommendation

Circular economy (CE), introduced first by (Pearce et al., 1990), has gained much momentum due to the recent increasing pressing need for achieving a sustainable socioeconomic system. As recent activities lead the increasing environmental hazards (air, soil, water pollution, biodiversity loss, animal extinction), resource depletion, excessive land use and economic instabilities (Brennan et al., 2015; Geissdoerfer et al., 2017). Early pieces of literature mainly emphasized a closed-loop industrial economy. CE concept has been interpreted in several ways and many scopes, ideas, and features have been added. Ellen MacArthur Foundation framed CE as an 'industrial economy that is restorative and regenerative through intension and design' (The Ellen MacArthur Foundation, 2013). (Geissdoerfer et al., 2017) defined CE as the regenerative system that minimizes resource input, waste, and energy output by closing, slowing, and narrowing resource supply. The CE initially attributed to holding 3R principles (Recycle, Reuse and Reduce) which is now extended to 10 strategies (recover, recycle, repurpose, remanufacture, refurbish, repair, reuse, reduce, rethink and refuge) (Morseletto, 2020). This can bend the traditional linear economy (take, make, use and dispose of) (Sharma et al., 2021). Germany first introduced CE as national law in early in 1996 followed by Japan and China in 2002 and 2009 respectively. EU also incorporated CE as a sustainable waste management system in 2015. The USA seems to lag in enacting CE in waste management regulation (Geissdoerfer et al., 2017; Morseletto, 2020). So does Bangladesh as there is no regulation for CE currently nor any govt. or NGO approach for attaining sustainable HCWM. No HCFs have their developed model integrating safe HCWM with CE.

Implementation of CE to the medical waste management system is way more complicated and challenging than other sectors as it contains hazardous (infectious, radioactive, pharmaceutical, sharp, chemical) substances and is due to single-use mind setup by HCFs. This is the reason for overlooking CE in HCWM (Antoniadou et al., 2021; Ranjbari et al., 2022; Sharma et al., 2021). For developing a sustainable management scenario for the MWM system, the first strategies of CE should be applied to minimize the waste generation as low as possible by smarter product use and manufacture (refuse, rethink and reduce). Minimization is preferred mostly as lower waste production leads to lower costs for waste management and increases efficiencies of material uses. Every HCFs should form a team that will develop strategic actions and procedures for HCWM based on

Fig. 8. Impact potential of HCWM (a, b, c & d showing effects of GW, HT, FWAET & TET respectively for four scenarios, S1 to S4) (Alam and Mosharraf, 2020).

monitoring material use to disposal, smart purchasing based on life cycle assessment of items, environmental effects (toxicity), disposal cost, reusability, and recyclability of materials. For example, prioritizing recyclable plastic made of polyethylene, or polypropylene rather than PVC (Cosimato and Vona, 2020; Voudrias, 2018; WHO, 2014). Cloth-based masks can be used instead of single use face masks which is creating negative environmental effects. While purchasing, non-recyclable plastics should be ruled out if sustainable alternatives are available.

The 2nd preferable option is to extend the lifespan of the materials or parts of materials by using them again or by another process (repair, refurbish, remanufacture, repurpose). A strict segregation technique as well as separate collection have to be implemented to differentiate hazardous, non-hazardous and reusable, and recyclable substances. This caution will reduce the risk associated with handling HCW. Reusing in the health sector is challenging and associated with the risk of infection and transmission of diseases. Proper classification of reusable material and disinfection techniques (steam sterilization or chemical sterilization) should be implemented before considering any item to be reusable. It is found that 41 % of Canadian hospitals reuse certain types of materials (WHO, 2014). Reusability of medical items greatly depends on the effectiveness of decontamination and sterilization and purchasing non-single-use reusable items. This step reduces the cost associated with HCWM and the amount of waste generation. For example, (Kwakye, 2011)estimated a reduction of 15,500 kg/year of waste and 175,000 US dollars/year in a 1000-bed hospital just reusing reusable sharp containers.

Recycling and recovering (heat and energy) are the last strategies that can be undertaken before disposal (Morseletto, 2020; Sharma et al., 2021; WHO, 2014). A huge amount of non-hazardous materials containing paper, cardboard, packaging, plastic wrapping, container, plastic pipes, and tubes can be successfully recycled. In Nepal, a study reported that recycled plastics, paper, and metal covered 40 % cost of waste management (WHO, 2014). The recyclable amount is tabulated in Table S4. Smurfit Kappa takes the paper wastage generated in England as recycled paper (Smurfit Kappa, 2022). A hazardous substances containing plastics, tubes, metals, and glass can be recycled after being disinfected. Food wastes, fabrics, and biodegradable items can be used for composting and also can be used as a great source of heat for the HCFs going through the incinerator. Recently, Lafarge-Surma Bangladesh introduced the Geocycle technique in which all types of MSW, food wastes, and MW are directly fed into the kiln for clinker production (Lafarge-Surma, 2022). In Bangladesh, Prism only recovers and recycles sharp, plastic, and metal substances after disinfection but their capacity is low (Shah et al., 2021a, 2021b, 2021c; Shafi et al., 2021; Subhan and Rahman, 2022; Rahman et al., 2019). The fly ash and bottom ash resulting from the incinerator can be integrated into the cement industries. This ash contains high levels of metals that can be recovered (Ranjbari et al., 2022). Recycling and recovery can sometimes lead to the use of excessive amounts of energy, technology, and cost associated with it which makes it less favorable (WHO, 2014). All these general considerations that are needed for an integrated sustainable MWM are summarized in Fig. 10. A model is developed for sustainable HCWM in the context of CE in Fig. 9. This general model can be implemented for attaining a sustainable MWM system. The 3R block (Rethink, Refuge, and Reduce) in Fig. 9 has to be considered in both manufacturers' and HCFs' ends. The manufacturers should be pushed by the government and other international agencies to develop, offer and marketize environmentally friendly sustainable products for the HCFs. On the manufacturers' end, they should also maintain these 3R principles i.e. avoiding unnecessary plastic wrappings, using reusable bags made from cloths, papers, cardboard, etc., rethinking their production and delivery processes, and refusing and reducing harmful ingredients. The HCFs on the other hand, as stated earlier and given in Fig. 10, should revisit, revise and rethink their purchasing procedures as well as priority items for waste minimization and extending lifespan.

Separate collection is crucial for the sustainable MWM model which can become more critical in situations like the Covid-19 pandemic. As stated in Section 6, color-coded separation will help to reduce occupation risks associated with the typical segregation process as well as it will be easier to distinguish between recyclable and non-recyclable items. Some materials like papers, glass, tubes, wrappings, fabrics, etc. can be directly recycled to manufacturers and some items which may contain infectious elements should undergo proper disinfection procedures before recycling as well as reusing. General biodegradable wastes can either go through composting or can go to in energy recovery section (Fig. 9). HCFs may construct their personal recovery unit, treatment unit, and waste-to-energy units or separate entities can be formed (public or private organizations) that will handle the MW produced in the HCFs. To attain the best of the CE model, strong supply chain management has to be implemented among the manufacturers, HCFs, and the private or public MWM organizations. As occupational and risks for disease transmission are possible in every step of MWM, well-defined strategical plans, regular inspection, and regulation, and strictly maintained disinfection procedures are needed.

CE for HCWM still lacks enough research, innovative technology, and approaches for delivering high-quality healthcare with sustainable waste generation, management, and circulatory use of waste. Every solution and technique should be weighted with its cost, affordability, and

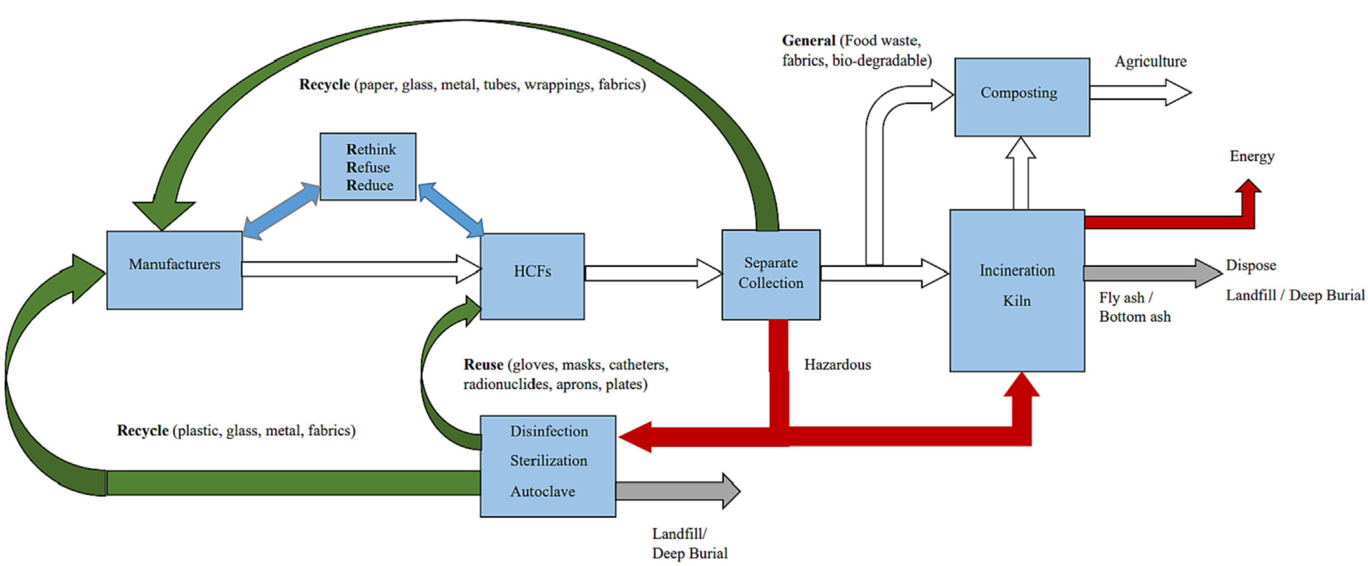

Fig. 9. A proposed CE model for sustainable HCWM system.

Fig. 10. Steps and considerations that are required for developing a CE model in HCFs.

environmental impact using sustainability assessment tools such as life cycle assessment (LCA), exergy evaluation, and ecotoxicity assessment (Ranjbari et al., 2022; WHO, 2014). Bangladesh is currently lacking a systematic and strategic approach for the MWM system as discussed in the previous sections, so applying CE in MWM will be 2nd priority after the proper management of hazardous materials. For implementation in Bangladesh, the responsible govt. authorities (DGHS, DoE) with private companies and NGOs should step forward to develop an integrated CE model for HCWM. The proposed CE model of this study is only possible if public-private partnership is introduced in the MWM system. The main obstacle that can be faced is ignorance of the stuff associated with the HCWM system. Proper training and regular regulation should be implemented in the HCFs. More research allocation should be provided for carrying out innovative research in this field so that private companies can be made interested to come forward with industrial applications.

9. Conclusions

This study complied all the primary and secondary information available about medical waste generation, existing practices in the HCFs, and legislation in Bangladesh. In comparison to developed and other Asian countries, Bangladesh lacks effective administration and facilities, as well as an implementation difficulty of existing legislation due to the lack of proper collaboration between health care organizations and the government. The model used in this study predicts that Bangladesh will more likely to generate a total of 50,000 tons of MW in 2025 where 12,435 tons is hazardous waste with a 1.25 kg/bed/day rate. From the handling of Covid patients, test kits, and vaccination from March 2020 to May 2022, a total of 82,553, 168.4, and 2300 tons of medical waste is estimated to have been generated during this period. Some recommendations are provided in this study after undergoing LCA and circular economy framework. Thus, this study can help the researchers and the policy makers to choose the best possible options for attaining sustainable medical waste management.

CRediT authorship contribution statement

All authors equally contributed to designing and writing the manuscript.

Data availability

The data that has been used is confidential.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.162083.

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