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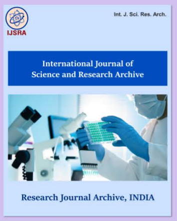

(Research Article)

Health consequences of inadequate solid waste management in Bangladesh: pollution, disease, and contamination risks

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Abstract

This study investigates landfill leachate contamination at six major landfill sites in Bangladesh such as Dhaka City Corporation (DCC), Chattogram City Corporation (CCC), Khulna City Corporation (KCC), Sylhet City Corporation (SCC), Rajshahi City Corporation (RCC), and Barishal City Corporation (BCC) by analyzing existing published data. The focus is on evaluating the impact of leachate on local water bodies and edible plants. A systematic search of databases including ScienceDirect, Scopus, PubMed, and Google Scholar from 2000 to 2023 was conducted using terms such as landfill leachate, contamination, heavy metals, and health risk assessment. The search adhered to PRISMA guidelines to ensure comprehensive literature coverage. Data collected involved leachate composition, waste production rates, and management practices through standardized sampling protocols, municipal statistics, and field surveys. Analytical methods included physical sorting and weighing of waste, as well as chemical analyses for Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and heavy metal concentrations using atomic absorption spectroscopy and inductively coupled plasma mass spectrometry. The study also evaluated waste treatment technologies like membrane bioreactors, pyrolysis, gasification, and, incineration assessing their efficiency in pollutant removal, energy recovery, and by-product quality. This research highlights the significant contamination issues posed by landfill leachate, providing insights into its impact on environmental and human health, and underscores the need for improved waste management and treatment technologies in Bangladesh.

Keywords: Landfill leachate; Health risks; Municipal solid waste; Waste management; Bangladesh; Waste treatment technologies

1 Introduction

The rapid increase in population and dynamic economic activities both within and beyond cities have led to significant challenges in waste management. In Bangladesh, annual waste generation is sharply rising due to rapid population growth, urbanization, and industrial development [1]. With over 522 urban centers producing substantial amounts of municipal solid waste (MSW) daily [2, 3] the country faces challenges in MSW management due to insufficient infrastructure and research [4, 5]. This situation is exacerbated by issues in waste collection, management, and energy recovery, underscoring the urgent need for efficient systems to mitigate environmental and health impacts, as highlighted by the World Bank's (2018) global snapshot of solid waste management [6].

Globally, 2.1 billion tonnes of municipal solid waste (MSW) were generated in 2023, with projections indicating further increases in the coming years [7]. By 2050, global waste is expected to rise from 2.01 billion tons to 3.40 billion tons annually [6]. The report *What a Waste 2.0* provides comprehensive insights into waste generation, management costs, and regulations extending to 2050 [6]. Solid waste discharge globally was 10.4 billion tons in 2010 and is projected to

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reach 148 billion tons by 2025, with developing countries contributing approximately 56% of the world's solid waste [8, 9]. While per capita waste generation rates are higher in developed nations, total waste generation is greater in developing countries [10, 11]. Proper waste management can transform waste into valuable resources, alleviate pressure on natural resources, and create new jobs [4, 12].

Effective waste management requires significant economic investment but offers benefits such as improved resource efficiency and reduced emissions. Modern waste-to-energy technologies, including controlled combustion, aim to convert waste into [6]. Energy efficiency programs help avoid natural resource depletion, improve environmental quality by reducing greenhouse gas (GHG) emissions, decrease reliance on fossil fuels, enhance energy security, mitigate energy shortages, and boost productivity by cutting operational costs (European Commission, 2016). Enhanced energy efficiency supports developing nations in achieving long-term growth objectives and focusing on reducing CO_2 emissions [13, 14]. Energy plays a crucial role in a country's economic performance and is also a significant contributor to global warming [15]. Therefore, energy efficiency has become a key policy tool for advancing decarbonized economic development and combating climate change [16].

Waste is categorized into hazardous (e.g., industrial, medical, e-waste) and non-hazardous materials (e.g., household garbage). Effective management of organic waste through composting can enhance crop yields, reduce fertilizer use, promote job creation, and lower emissions [17, 18]. However, challenges such as inefficient collection, high removal costs, and limited recycling policies persist [19]. While advanced countries use technologies like composting, incineration, and recycling to manage MSW, developing countries often rely on rudimentary dumping methods [20, 21]. Pyrolysis and hydrothermal carbonization (HTC) offer promising waste-to-energy solutions but face challenges such as variable heating rates and limited adoption [22, 23].

In Bangladesh, solid waste is primarily disposed of by dumping non-segregated materials into landfill sites [24, 25, 26, 27], a practice also seen in certain developed nations [28]. Cities such as Dhaka, Chattogram, Rajshahi, Barishal, and Khulna are grappling with severe waste management challenges due to the limitations of traditional landfill approaches. Rapid population growth and dynamic economic activities in these cities have intensified waste management issues [29]. The adoption of modern waste-to-energy technologies is being explored as a means to enhance waste management and environmental sustainability [6].

Effective municipal solid waste (MSW) management is a significant environmental challenge, particularly in developing countries [30, 17, 31, 32]. Advanced nations utilize various technologies for MSW management, including composting, anaerobic digestion, incineration, pyrolysis, gasification, and recycling, with any residual waste being directed to modern landfills [20, 33]. These countries also focus on advancing technologies for recycling and resource recovery [12]. Conversely, many developing nations rely on basic dumping methods and partial, uncontrolled treatment for resource recovery [21].

Solid waste management is a global concern with widespread impacts. Poorly managed waste can contaminate oceans, cause flooding, spread diseases, exacerbate respiratory problems, harm wildlife, and hinder economic development, including tourism. As economies grow and urbanize, waste generation increases, complicating collection and disposal efforts. Waste management can become a significant budgetary expense, with low-income countries spending about 20% of municipal budgets on it, middle-income countries over 10%, and high-income countries around 4% [6]. To mitigate health risks associated with solid waste management practices, it is crucial to understand the links between exposure sources, environmental pathways, and health outcomes [34]. Many hazardous compounds leach from MSW landfills, presenting serious risks to human health and the environment, and some hazardous substances have been found in sediments but not in leachates.

The open burning of plastics is linked to an elevated risk of various health issues, including heart disease, respiratory problems, neurological disorders, nausea, skin rashes, numbness or tingling in the fingers, headaches, memory loss, and confusion [35-41]. The media and public discourses often focus on marine plastics, plastic litter, and microplastics [42]. Despite existing regulations, the open burning of plastic waste remains a significant global health and environmental hazard. This article explores local practices in India, Indonesia, the Philippines, and Zambia and proposes harm reduction strategies targeting the most toxic plastics [43].

In 2023, global CO_2 emissions related to energy rose by 1.1%, reaching an all-time high of 37.4 billion tonnes an increase of 410 million tonnes from the previous year. This uptick was partly due to reduced hydropower output caused by droughts, which contributed roughly 170 million tonnes to the emissions total. Coal emissions were responsible for more than 65% of this increase. Although emissions grew by 900 million tonnes from 2019 to 2023, the expansion of critical clean energy technologies, such as solar PV, wind, nuclear, heat pumps, and electric vehicles, helped temper the increase, preventing a threefold rise [44]. The *World Energy Outlook 2023* offers a comprehensive analysis of the global energy system amidst geopolitical tensions and unstable markets. It highlights how structural changes in economies and energy use impact global energy demand, reviews energy security fifty years post-IEA's foundation, evaluates necessary actions for COP28 to pursue the 1.5 °C climate goal, and discusses current energy trends in investment, trade, electrification, and energy access [45].

Excessive CO_2 emissions from fossil fuel consumption are contributing to global warming. CO_2 capture and utilization (CCU) is a promising solution, but challenges such as high costs and limited utilization persist. Utilizing solid wastes, such as steel slag and fly ash, for CCU offers a cost-effective method for CO_2 fixation and utilization [46]. To enhance CO_2 capture efficiency, selectivity, and reduce operational costs, various CO_2 capture reagents both molecular and solid materials have been developed [47-50]

Leachates from municipal solid waste (MSW) continue to be a significant source of toxic contaminants, impacting freshwater aquatic life [51, 52]. The open burning of plastics, waste materials, fossil fuels, and wood generates harmful gases such as carbon dioxide (CO_2), carbon monoxide (CO), particulate matter (PM), sulfur oxides (SO_x), and nitrogen oxides (NO_x), which contribute to air pollution [53, 54, 55]. This study aims to address gaps in the current understanding of municipal solid waste management in Bangladesh, with a focus on enhancing collection, treatment, and disposal practices, and investigating advanced waste-to-energy technologies. By tackling both environmental and health issues associated with existing methods, the research intends to offer practical recommendations to improve waste management strategies and reduce their negative impacts.

2 Search and Retrieval Methodology

This study analyzed published data on landfill leachate from four significant landfill sites in Bangladesh: Amin Bazar and Matuail in Dhaka, Mogla Bazar in Sylhet, and Rowfabad in Chattogram [17, 24, 25, 56]. These sites represent key locations within major metropolitan areas of the country, including Dhaka, Chattogram, Rajshahi, Sylhet, and Barishal.

To identify relevant scientific articles, we conducted a systematic search across publicly accessible databases including ScienceDirect, Scopus, PubMed, and Google Scholar, covering the period from 2000 to 2024. We employed search terms such as "landfill leachate," "surface and groundwater contamination," "heavy metals," "health risk assessment," "developing countries," and "Bangladesh." References from these articles were reviewed to locate additional pertinent studies. The literature search and article retrieval followed PRISMA guidelines [57, 58].

We compiled and reviewed the data to assess the status of landfill pollution in Bangladesh over the past decade, focusing on its impact on nearby water bodies. Additionally, we analyzed the published data to understand leachate pollution levels and associated health risks. Although landfills are present in every municipality in Bangladesh, this review is limited to the four sites mentioned due to the availability of detailed studies.

2.1 Study Areas

The study encompasses the major divisions of Bangladesh, focusing on waste management and the associated health hazards, as illustrated in the map.

2.1.1 Dhaka

The population of Bangladesh's capital, Dhaka, ranges between 6.73 and 7.5 million. In 2005, the city produced roughly 5,000 tons of solid garbage per day (0.56 kg per capita per day), with estimations indicating that this amount might approach 30,000 tons per day by 2020 [6,59]. The city has two significant landfill sites: Amin Bazar and Matuail. The Amin Bazar landfill (23°47′48″N, 90°17′50″E) is situated in the low-lying floodplains of the Karanachhali River, Savar Upazila.

2.1.2 Chattogram

Chattogram, located in Bangladesh's southern region, is home to around 2.66 million people. In recent years, the city produced approximately 1,161-1,548 tons of solid trash per day, with an average of 0.34-0.48 kg per individual [6, 19]. The Rowfabad landfill (22°18′45.9″N, 91°46′22.3″E) is a 2.83-acre facility near the Bay of Bengal.

2.1.3 Rajshahi

Rajshahi, located in Bangladesh's northwest area, has a population of around 1.1 million. In 2020, the city generated approximately 500 tons of solid trash per day, with an average generation rate of 0.45 kg per person per day [60].

Rajshahi Municipal Solid rubbish Landfill (24°22′50″N, 88°36′15″E) manages rubbish generated by the city's inhabitants.

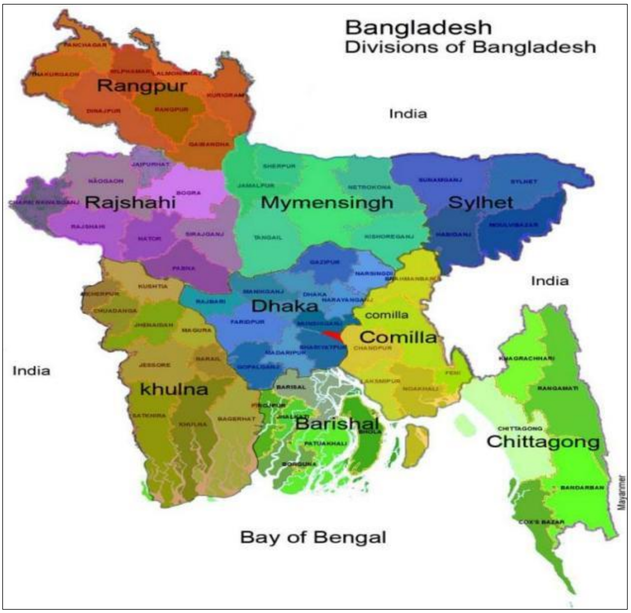

Figure 1 Map of Studied area of Bangladesh

2.1.4 Barishal

The Barishal Municipal Solid trash Landfill (22°43′0″N, 90°22′0″E) is located on the city's outskirts and plays an important role in managing trash. However, it confronts obstacles, most notably flooding during the monsoon season. The survey found that the following sources contributed to overall garbage generation: residential (79.6%), commercial (15.5%), industrial (1.2%), street sweeping (1.5%), and health care facilities (3.8%) [61].

2.1.5 Khulna

The Khulna Solid trash Management Facility (22°50′30″N, 89°33′20″E) manages the city's trash and is situated in an area with high industrial activity. The private sector in Khulna handles 38.80 tons of solid garbage per day, accounting for 7.65% of the city's total waste and generating 13.4 million BDT yearly. Jahan (2023) used a system dynamics model to forecast the rate of municipal solid trash generation in 2050. The study showed that residential garbage generation averages 0.472 kg per person each day. The garbage is mostly biodegradable (81%), which emphasizes the significance of frequent collection and composting. Furthermore, paper (6.67%) and plastic (4.74%) account for significant percentages of the garbage [62].

2.1.6 Sylhet

The findings show that solid waste generation in Sylhet city rose to nearly 260 tons per day in 2017, marking a 2.5-fold increase from 2004 [63]. Currently, with a population of about 1 million and an area of 79.50 km^2, the city produces 375 tons of garbage daily, a figure projected to increase to 890 tons by 2040 [64, 65]. To tackle these issues, improvements in waste management infrastructure and increased public awareness are essential. Future research should investigate CO2 trends related to waste management and their effects on air quality and public health.

2.2 Data Collection

Data was collected through a multi-faceted approach to ensure comprehensive coverage of leachate composition, waste production rates, and management practices. For leachate composition, samples were obtained from various landfills, including Rowfabad and Matuail, using standardized sampling protocols to ensure representative data. Waste production rates were assessed by reviewing municipal waste generation statistics and conducting field surveys across major urban areas. Additionally, information on waste management practices was gathered through interviews with local waste management authorities and field observations.

2.3 Analytical Methods

To analyze waste composition, a combination of physical and chemical analysis techniques was employed. Physical components were quantified through sorting and weighing of waste samples, while chemical analysis involved measuring parameters such as Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), and heavy metal concentrations using techniques like atomic absorption spectroscopy and inductively coupled plasma mass spectrometry. Evaluation of waste treatment technologies included assessing the efficiency of various methods, such as membrane bioreactors, pyrolysis, and gasification, through performance metrics like pollutant removal rates, energy recovery, and by-product quality. These analyses were complemented by case studies and feasibility assessments to determine the practical applications and effectiveness of the technologies in different contexts.

3 Overview of Waste Generation and Management in Bangladesh

This section provides an overview of waste generation and management in Bangladesh, focusing on the current situation regarding waste production, composition, and characteristics. To assess the current scenario of waste generation and management, the research evaluates pollution, contamination, and their impacts on human health and the environment, with a particular emphasis on Tables 1 through 4.

Table 1 outlines the state of waste management in Bangladesh, with key statistics from 2005. Urban areas generated approximately 4.87 million tons of municipal solid waste annually, with Dhaka alone contributing 3,000 tons per day. Agricultural waste amounted to 65 million metric tons per year, while industrial waste included 109.47 million cubic meters of wastewater and 26,884 tons of solid waste. Hazardous medical waste totaled 12,271 metric tons. Per capita waste generation ranges from 0.41 kg/day in urban areas to 1.68 kg/day in agriculture. Projections suggest that solid waste generation will increase to 17.16 million tons annually by 2025. Currently, waste collection is inconsistent, with much of the waste ending up in uncontrolled landfills and limited recycling or hazardous waste management. E-waste figures include 22 million mobile phones and 1.25 million televisions, with only 15% of Dhaka's waste being recycled by the informal sector. This situation underscores the urgent need for enhanced formal waste management systems.

Table 1 Current Situation of Wastes in Bangladesh – At a Glance

Category	Statistics	Sources of data
Total Volume of Wastes (tons/year)	Total volume of municipal solid wastes in urban areas: 4,866,505 (2005) = 13,332.89 tons/day × 365 3,000 tons/day in Dhaka (2005)	[66, 67]
Agricultural Waste	65 million metric tons per year	[66]
Industrial Waste (hazardous)	109.47 million cubic meters/year (waste water); 0.113 million tons/year (sludge); 26,884 tons/year (solid waste)	[68]
Hazardous Medical Waste	12,271 metric tons per year (2007)	[68]
Waste Per Capita (kg/day)	Urban: 0.41 (2005); Dhaka City: 0.56 (2005); Agricultural: 1.68 (based on 2008 rural population)	[67, 69]
Future Waste Projections (Total Waste Generation)	By 2025 (solid waste)17,155,000 tons/year = 47,000tons/day x 365 0.60 kg/per/day in Urban Areas 2012 (hazardous waste) 2, 472.07 million/cubic meter/year (waste water), 2.81 million metric ton/year (sludge) and 53,874 metric ton/year (solid waste)	[69]
Solid Waste Management	Collection of waste (% of waste generated): 44.30% - 76.47% in major urban cities; 43.5% for Dhaka City	[66, 67]
Solid waste disposal facilities	Mainly uncontrolled land-filling (except for the sanitary landfill at Matuail site in Dhaka, supported by JICA). No site or facility for treatment, recycling and disposal of hazardous waste.	[67]
E-Wastes	Mobile phones: 22,000,000 Personal computers: 600,000 Televisions: 1,252,000	[69]

Recycle	Informal Sector: 120,000 urban poor from the informal sector are involved in the recycling trade chain of Dhaka City. 15% of the total generated waste in Dhaka (mainly inorganic) amounting to 475 tons/day are recycled daily.	[66]

Table 2 represents the distribution of solid waste across six major cities in Bangladesh. Dhaka City Corporation (DCC) generates the highest volume of waste at 5,340 tons per day, followed by Chattogram City Corporation (CCC) with 1,315 tons, and Khulna City Corporation (KCC) with 520 tons. Rajshahi City Corporation (RCC), Barishal City Corporation (BCC), and Sylhet City Corporation (SCC) produce 170, 130, and 215 tons per day, respectively. The predominant waste category across all cities is organic matter, totaling 5,409 tons, with Dhaka contributing significantly to this figure. Other notable waste categories include paper (792 tons), plastic (303 tons), and miscellaneous items (722 tons). The per capita waste generation ranges from 0.325 kg/day in Barishal to 0.485 kg/day in Dhaka, highlighting variability in waste production across cities.

Table 2 Production of Different Categories of Solid Waste in the Six Major Cities of Bangladesh [70]

Waste Category	**DCC**	**CCC**	**KCC**	**RCC**	**BCC**	**SCC**	**All Waste Streams**
Organic matter	3,647	968	410	121	105	158	5,409
paper	571	130	49	15	9	18	792
plastic	230	37	16	7	5	8	303
Textile and wood	118	28	7	3	2	5	163
Leather and rubber	75	13	3	2	1	1	95
metal	107	29	6	2	2	2	148
glass	37	13	3	2	1	2	58
others	555	97	26	18	5	21	722
total	5340	1315	520	170	130	215	7,690
Per capita kg/day	0.485	0.360	0.347	0.378	0.325	0.430	0.387

Note: DCC = Dhaka City Corporation, CCC = Chattogram City Corporation, KCC = Khulna City Corporation, RCC = Rajshahi City Corporation, BCC = Barishal City Corporation, SCC = Sylhet City Corporation.

3.1 Physical Components of MSW

Dhaka generates significantly more municipal solid waste (MSW) than other cities, with higher chemical component levels (Table 2 and 3). Chattogram City Corporation (CCC) has higher volatile solids due to its lower socioeconomic status [71, 72], which can enhance calorific value and soil fertility [6]. However, variations in sampling methods lead to differences in reported chemical compositions. For instance, Halder, *et al.* (2014) [73] reported MSW in Rajshahi with 50.2% carbon and 1.9% nitrogen, while another researcher found slightly different values. A high carbon-to-nitrogen (C/N) ratio suggests potential for organo-mineral fertilizers [70].

In Bangladesh, MSW is mainly vegetable and food waste (67.7%), with paper at 9.7%, and plastics, leather, and rubber at 5.1% (Waste Concern, 2009). Dhaka's MSW varies from 54.9% to 68.3% VFW, and Chattogram's ranges from 62% to 72% VFW, influenced by socioeconomic factors [74, 75]. In Khulna, VFW constitutes 77.3% to 78.9% of MSW, while in Rajshahi, it ranges from 70% to 95.8% [76, 77].

3.2 Chemical Components

Differences in sampling and testing methodologies can lead to variations in reported chemical components of municipal solid waste (MSW). For instance, Halder, *et. al.,* (2014) [73] reported that MSW in Rajshahi contained 50.2% carbon, 1.9% nitrogen, 0.1% sulfur, 7.5% hydrogen, 40.2% oxygen, and 0.2% other elements. Despite such discrepancies, the high carbon-to-nitrogen (C/N) ratio of MSW, as shown in Table 4, highlights its substantial potential for producing organo-mineral fertilizers [70].

High volatile solids in MSW can contribute to an increased calorific value. However, the average moisture content (MC) of MSW in Bangladesh is notably high, as detailed in Table 4. The organic component of MSW in six major cities contains average levels of 0.8% nitrogen, 0.3% phosphorus, and 0.7% potassium [70]. These elevated nutrient levels suggest that composted MSW could enhance soil fertility when used as a fertilizer.

Vongdala, *et al.* (2019) [55] evaluated heavy metal contamination, including cadmium (Cd), chromium (Cr), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn), in water, soil, and plants during both dry and wet seasons. Their contamination levels were compared with the standards set by the Agreement on the National Environmental Standards of Laos (ANESs), Dutch Pollutant Standards (DPSs), and the World Health Organization (WHO).

Table 3 Physical Composition of Municipal Solid Waste (MSW) and Waste Generation Rates (WGR) in Key Urban Centers of Bangladesh [71, 72]

Composition	**Wet weight %**						
	Dhaka city corporation (DCC)	**Chattogram city corporation (CCC)**	**Khulna city corporation (KCC)**	**Rajshahi city corporation (RCC)**	**Barishal city corporation (BCC)**	**Sylhet city corporation (SCC)**	**Average of wt %**
Foods, vegetables	68.3	73.6	78.9	71.1	81.1	73.8	74.5
Paper and its products	10.7	9.9	9.5	8.9	7.2	8.4	9.1
Polythene and plastics	4.3	2.8	3.1	4.0	3.5	3.4	3.5
Textile and wood	2.2	2.1	1.3	1.9	1.9	2.1	1.9
Rubber and leather	1.4	1.0	0.5	1.1	0.1	0.6	0.8
Metal and tins	2.0	2.2	1.1	1.1	1.2	1.1	1.4
Glass and ceramic	0.7	1.0	0.5	1.1	0.5	0.7	0.8
Brick, stone and concrete	1.8	1.1	0.1	2.9	0.1	1.8	1.3
Others (rope, bone, etc.)	1.9	1.2	1.2	1.3	1.3	2.8	1.6
WGR (waste generation rate)							
Population, in million	7.23	2.66	0.67	0.46	0.35	0.51	-
Waste generation (kg per capita per day)	0.70	0.56	0.48	0.27	0.44	0.25	0.3

The major cities in Bangladesh including Dhaka, Chattogram, Rajshahi, Khulna, Sylhet, and Barishal collectively generate 7,690 to 8,000 tons/day of municipal solid waste (MSW), with Dhaka accounting for around 70% of this total [19, 70].

In 2005, Dhaka produced 4,000 to 5,000 tons/day of MSW, averaging 0.56 kg/cap/day, with about 50% uncollected [75, 78]. Chattogram generated 1,161 to 1,548 tons/day, averaging 0.34 to 0.48 kg/cap/day, with 58% uncollected [10, 78]. Khulna produced 321 to 520 tons/day, averaging 0.27 to 0.6 kg/cap/day, with an expected increase to 950 tons/day by 2025 [79, 80]. Rajshahi generated 170 to 195 tons/day, averaging 0.25 to 0.3 kg/cap/day [78, 81]. Sylhet produced 143 to 250 tons/day, averaging 0.3 to 0.45 kg/cap/day, with an increase from 100 tons/day in 2004 to 250 tons/day in 2016 [72, 82].

Table 4 Chemical properties of municipal solid waste (MSW) in urban Bangladesh [71, 83]

Parameters	**Dhaka city corporation**	**Rajshahi city corporation**	**Khulna city corporation**	**Barishal city corporation**	**Sylhet city corporation**	**Chattogram city corporation**
pH	8.69	7.72	7.76	7.70	7.71	8.23
MC (%FM)	70	56	68	57	69	62
C/N	10.17	12.15	16.08	12.44	11.96	17.22
Ash residue (%DM)	29	52	44	57	35	46
N_{total} (%DM)	0.89	0.56	1.62	1.23	0.90	0.17
Volatile solid (dead animal matters, plants and synthetic organic compound, % DM)	71	48	56	43	65	54
K_{total}(%DM)	0.62	0.38	1.37	1.18	0.42	0.57
P_{total}(%DM)	0.31	0.31	0.41	0.40	0.32	0.23

*DM = Dry matter; FM = Fresh matter.

3.3 Comparative Analysis of Pollutant Concentrations and Impacts at Rowfabad and Matuail Landfills

Kathpalia and Alappat, (2005) [84] illustrated the data compares concentrations of various pollutants and their weighted importance at Rowfabad and Matuail landfills. For Rowfabad, the most significant pollutants are Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD), with high concentration values and substantial impact scores. Arsenic (As) and Chromium (Cr) have notable concentrations, though their impact scores are moderate due to lower weighting factors. In contrast, Matuail Landfill shows higher concentrations of COD and ammonia nitrogen, which significantly affect the overall impact. Concentrations of pollutants like lead (Pb) and zinc (Zn) are lower in Matuail compared to Rowfabad, but their relative importance remains consistent. Overall, the data highlights COD and ammonia nitrogen as critical pollutants at their respective sites, underlining their substantial environmental impact.

4 Thermal Treatment for Waste Management: A Sustainable Approach

Thermal treatment of municipal solid waste (MSW) is gaining traction for its ability to reduce waste volume by up to 90%, recover energy, and eliminate hazardous substances. This method alleviates landfill pressures, produces valuable by-products like bio-oil and syngas, and reduces methane emissions, though managing air emissions is crucial [56, 85]. In Bangladesh, techniques such as pyrolysis, gasification, and incineration are being explored to address energy and waste management challenges. Pyrolysis converts waste into liquid fuels and is effective with feedstocks like rice straw and plastics. Gasification, a newer approach in Bangladesh, shows potential for power generation from agricultural and organic residues. Incineration reduces waste volume and enhances recycling rates but faces financial and logistical hurdles [86]. Given the country's power crisis and limited grid connectivity [73, 87], utilizing MSW biomass for renewable energy presents a viable solution. Although still emerging, these sustainable energy practices offer promising avenues for addressing Bangladesh's energy and environmental challenges [88, 89, 90, 91]

4.1 Pyrolysis

Pyrolysis is a thermochemical process that treats municipal solid waste (MSW) in the absence of oxygen, using nitrogen as a fluidizing gas and applying external heat [56, 92]. This technique is effective for producing liquid fuels from feedstocks such as rice straw, jute stick, and bagasse. Optimal results are achieved with rice straw at 450°C in a fluidized bed reactor, while rice husk at 480°C yields 40% liquid, 35% char, and 25% gas [93]. Sugarcane bagasse also shows high liquid yield at 475°C [94]. Additionally, waste paper and plastics demonstrate high liquid yields at 450°C and 350°C, respectively [95, 96]. Pyrolysis of solid tire waste (STW) at 475°C produces a significant liquid yield, with the highest yield from motorcycle tires [97, 98]. A pilot-scale STW reactor achieved 49% liquid yield at 430°C, and a small-scale commercial plant in Gazipur produced 45% oil with a heating value of 44 MJ/kg [99]. Medium-scale plants are economically more viable for crude oil production compared to smaller or pilot-scale setups, and STW char can be used for high-quality briquettes [100].

4.2 Gasification

Gasification transforms biomass and organic solid waste (OSW) into syngas and solid char by reacting them with controlled amounts of oxygen and/or steam at temperatures above 700°C [101]. While relatively new in Bangladesh, this method holds significant promise for power generation. For instance, agricultural residues, forest residues, and municipal solid waste (MSW) could potentially produce 1178 MW, 250 MW, and 100 MW of power, respectively [86]. In Kapasia, Gazipur, a 250 kW gasification plant utilizes rice husks to generate 470 kW of electricity, cutting CO_2 emissions by 12,236 tonnes over ten years [102]. Additionally, gasification of bagasse could produce around 100 MW, which could support the sugar industry or be fed into the national grid [86].

4.3 Incineration

Incineration is effective in reducing municipal solid waste (MSW) volume by up to 90%, decreasing pollution, and improving recycling rates while reducing dependence on fossil fuels [17, 23]. Waste-to-energy (WtE) technologies offer a sustainable solution, although Dhaka's plans for two 50 MW WtE plants have not yet materialized, and proposals from China are still in early stages [103]. The renewable energy potential from MSW in Bangladesh is projected to reach 4173.9 to 5645.3 GWh by 2030 and 6582.5 to 11579.2 GWh by 2050 [104]. WtE plants can recover energy, reduce greenhouse gas emissions, and conserve land, but financial viability is challenged by MSW's low calorific value and high moisture content [105]. In Dhaka, MSW could potentially generate about 100 MW of electricity, with an REP of 1399.6 to 1712.9 GWh by 2030 and a reduction of 1.18 to 1.44 MT CO_2eq. Similarly, Chattogram could support a 5-8 MW WtE plant with an REP of 762.7 to 900.3 GWh and GHG reductions of 0.64 to 0.76 MT CO_2eq [106]. Khulna and Rajshahi could produce significant daily energy outputs from MSW and agricultural residues [77].

5 Carbondioxide (CO_2) emissions overview of Bangladesh

From 1971 to 2016, fossil CO2 emissions in Bangladesh soared from 3,098,785 tons to 74,476,230 tons. Emissions per capita increased from 0.05 to 0.47 tons, reflecting a growing carbon footprint. Although Bangladesh's global CO_2 emissions share peaked at 0.21% in 2016, the data highlights an urgent need for better emission reduction strategies due to rising total and per capita emissions amid a growing population [Table 5].

Table 5 Fossil Carbon Dioxide (CO_2) Emissions of Bangladesh (Sources: IEA, World Population Prospects, (EDGAR) 2019) [45, 107]

Year	Fossil CO_2 Emissions (tons)	CO_2 Emissions Change (%)	CO_2 Emissions per Capita	Population	Population Change (%)	Share of World's CO_2 Emissions (%)
2016	74,476,230	4.50	0.47	159,784,568	1.24	0.21
2015	71,265,882	8.41	0.45	157,830,000	1.20	0.20
2014	65,735,285	3.30	0.42	155,961,299	1.25	0.18
2013	63,632,915	4.52	0.41	154,030,139	1.28	0.18
2012	60,882,130	2.00	0.40	152,090,649	1.25	0.17
2011	59,686,924	0.02	0.40	150,211,005	1.23	0.17
2010	59,676,090	9.32	0.40	148,391,139	1.15	0.17
2009	54,587,614	8.64	0.37	146,706,810	0.88	0.15
2008	50,245,111	13.72	0.35	145,421,318	0.89	0.14
2007	44,184,934	8.90	0.31	144,135,934	1.06	0.12
2006	40,573,313	5.97	0.28	142,628,831	1.22	0.11
2005	38,285,911	9.56	0.27	140,912,590	1.53	0.11
2004	34,945,528	2.85	0.25	138,789,725	1.68	0.10

2003	33,976,199	4.70	0.25	136,503,206	1.76	0.10
2002	32,450,721	5.59	0.24	134,139,826	1.88	0.09
2001	30,732,365	17.88	0.23	131,670,484	1.92	0.09
2000	26,070,265	8.49	0.20	129,193,327	1.92	0.07
1999	24,029,929	6.68	0.19	126,754,824	1.93	0.07
1998	22,525,157	2.08	0.18	124,350,471	1.89	0.06
1997	22,065,250	8.75	0.18	122,039,226	1.80	0.06
1996	20,289,781	1.53	0.17	119,876,868	1.77	0.06
1995	19,984,193	22.63	0.17	117,793,338	1.88	0.06
1994	16,296,609	8.23	0.14	115,614,891	1.94	0.05
1993	15,057,802	5.85	0.13	113,418,757	1.93	0.04
1992	14,225,102	12.41	0.13	111,272,102	1.86	0.04
1991	12,654,205	-6.09	0.12	109,242,834	1.96	0.04
1990	13,475,083	5.88	0.13	107,147,651	2.15	0.04
1989	12,726,855	9.16	0.12	104,893,674	2.15	0.04
1988	11,659,413	5.39	0.11	102,688,833	2.19	0.03
1987	11,062,851	12.68	0.11	100,490,256	2.26	0.03
1986	9,817,517	11.00	0.10	98,271,746	2.41	0.03
1985	8,844,573	16.77	0.09	95,959,099	2.59	0.02
1984	7,574,138	4.31	0.08	93,534,239	2.73	0.02
1983	7,261,242	-5.92	0.08	91,045,478	2.81	0.02
1982	7,717,928	8.63	0.09	88,555,336	2.79	0.02
1981	7,104,506	-2.68	0.08	86,154,836	2.65	0.02
1980	7,300,458	12.79	0.09	83,929,765	2.47	0.02
1979	6,472,678	11.47	0.08	81,908,151	2.38	0.02
1978	5,806,784	7.55	0.07	80,007,550	2.39	0.02
1977	5,399,280	2.34	0.07	78,137,788	2.30	0.02
1976	5,275,855	7.29	0.07	76,380,080	2.25	0.01
1975	4,917,251	18.92	0.07	74,700,345	2.40	0.01
1974	4,135,021	6.93	0.06	72,947,807	2.53	0.01
1973	3,866,883	19.02	0.05	71,144,818	2.59	0.01
1972	3,249,039	4.85%	0.05	69,346,705	1.42	0.01
1971	3,098,785	-0.40%	0.05	68,376,204	1.24	0.01

6 Chemical reactions relevant to various waste management processes

6.1 Chemical Reaction in Waste Incineration

In waste incineration, organic matter combusts with excess oxygen, producing carbon dioxide (CO_2), water (H_2O), ash, and heat. The generalized reaction is:Organic matter (C_{org}) + Excess air (O_2) → CO_2 + H_2O + Ash + Heat; This exothermic process helps convert waste into energy (EPA, 2012) [108]

6.2 Detailed Chemical Reaction in Waste Incineration

The combustion of organic waste in incinerators can be summarized by the following reaction:

$$C_nH_mO_p + (n + 4m - 2p)O_2 \rightarrow nCO_2 + 2mH_2O + Ash + Heat$$

In this reaction n, m, and pare the numbers of carbon, hydrogen, and oxygen atoms in the organic compound, respectively. The combustion produces carbon dioxide (CO_2), water (H_2O), ash, and heat (EPA, 2012) [108].

6.3 Chemical Reaction in Anaerobic Digestion (Landfilling)

In anaerobic digestion, organic waste decomposes in the absence of oxygen, producing biogas and digestate:

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$

Where: $C_6H_{12}O_6$ represents glucose, a common organic component in waste. This process generates methane, which can be captured and used as an energy source, and carbon dioxide [109]

6.4 Chemical Reaction in Composting

In composting, organic waste decomposes aerobically to form compost. The overall reaction is:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + Compost$$

Where: $C_6H_{12}O_6$ represents glucose or similar organic material. This process breaks down organic material into compost, a valuable soil amendment [110].

6.5 Chemical Reaction in Recycling (Metals)

For metal recycling, such as aluminum, the reaction in the refining process is:

$$2Al_2O_3 + 3C \rightarrow 4Al^{+3} + 3CO_2$$

This reaction shows the reduction of aluminum oxide to produce aluminum metal and carbon dioxide [111].

7 Health Risks from Improper Solid Waste Management

Improper solid waste management poses severe health risks on multiple fronts. Air pollution from practices such as incineration and open burning releases harmful pollutants, leading to respiratory conditions like asthma and chronic obstructive pulmonary disease [94]. Inefficiently managed landfills and dumps generate leachate that contaminates water sources, causing waterborne diseases such as cholera and hepatitis . Soil contamination from leached waste, including e-waste and heavy metals, compromises agricultural safety and can lead to heavy metal poisoning (Environmental Protection Agency, 2012) [108]. Additionally, unmanaged waste serves as breeding grounds for disease vectors like mosquitoes and rodents, spreading malaria and dengue fever [70]. Proximity to waste sites also exposes residents to hazardous materials, resulting in skin infections, gastrointestinal issues, and mental health problems such as depression and anxiety [112].

7.1 Impact of Waste Management on Global Warming and Greenhouse Gases

Greenhouse gas (GHG) emissions from composting have been extensively quantified, totaling 1,287,786 tons of CO_2 equivalent (CO_2e) annually [71]. Dhaka, with the highest waste generation rate of 1,817,179 tons per year, contributes significantly with 20,611 tons of methane (CH_4) (433,581 tons CO_2e), 85,779 tons of carbon dioxide, and 4,814 tons of nitrous oxide (N_2O) (1,493,140 tons CO_2 e). Chattogram also shows notable emissions, with CH_4 and N_2O contributing

95,847 and 77,579 tons CO_2e, respectively. In comparison, Khulna and Rajshahi, having lower waste generation rates, exhibit reduced emissions, though Khulna's CH_4 emissions per ton of waste are high. Barishal and Sylhet show moderate emissions due to their smaller waste generation rates. The high global warming potentials of CH_4 and N_2O, being 21 and 310 times that of CO_2 respectively, highlight the need for enhanced waste management practices to mitigate climate change effects.

Municipal solid waste (MSW) is a significant GHG source in Bangladesh, with emissions estimated at 64.46 kg CO_2 per capita annually. Managing one ton of waste results in 420.88 kg CO_2 emissions [113]. In 2005, the average household of 4.72 people emitted 304.25 kg CO_2 per year, rising to 380.07 kg CO_2 by 2014 for a household of 4.40 people [113]. Increased GHG emissions have serious health implications, including heat-related illnesses, exacerbated respiratory and cardiovascular conditions, and the spread of diseases. Climate change also threatens food security and mental health.

8 Results and Discussion

The study assessed landfill leachate pollution at four major sites in Bangladesh—Amin Bazar and Matuail in Dhaka, Rowfabad in Chattogram, and Mogla Bazar in Sylhet—highlighting the complex waste management and environmental challenges faced by the country. The data, collected through systematic searches of scientific literature and direct analysis of waste and leachate samples, revealed significant variability in waste generation rates and leachate composition across these sites. Dhaka, generating the highest waste volume, faces severe contamination issues with high levels of Chemical Oxygen Demand (COD) and Biological Oxygen Demand (BOD), reflecting a substantial environmental impact. Rowfabad and Matuail landfills, in particular, showed elevated concentrations of pollutants like ammonia nitrogen and heavy metals, indicating potential risks to local water bodies and public health. The study also emphasized the need for improved waste management practices, noting that while thermal treatments such as pyrolysis and gasification offer promising solutions for waste reduction and energy recovery, they are not yet fully operational on a large scale. Furthermore, the analysis of greenhouse gas emissions highlighted the significant contribution of waste management to climate change, particularly through methane and nitrous oxide emissions. Addressing these issues requires enhanced infrastructure for waste management, better regulatory frameworks, and the adoption of sustainable technologies to mitigate both environmental and health impacts.

9 Conclusion

Improper solid waste management in Bangladesh poses substantial public health risks through the chemical reactions that occur during waste decomposition and pollution. The hazardous chemicals released from waste combustion, leachate contamination, and soil pollution contribute to severe health problems, including respiratory conditions, waterborne diseases, and chronic health issues related to heavy metals and e-waste. This research emphasizes the urgent need to address the severe impacts of landfill leachate and inadequate waste management practices.

Landfills such as Rowfabad and Matuail, which are heavily contaminated with pollutants, highlight the critical risks to public health and environmental sustainability. Rapid urbanization and increasing waste production further aggravate these issues, signaling the necessity for enhanced waste management strategies and advanced treatment technologies. Current practices are insufficient to manage the growing waste challenge effectively, making it imperative to explore and adopt technologies such as pyrolysis, gasification, and incineration, while balancing economic, environmental, and local considerations.

The study underscores the critical need for improved waste management strategies in Bangladesh to address the challenges of leachate pollution, health risks, and greenhouse gas emissions. Implementing advanced waste treatment technologies and enhancing recycling practices can significantly mitigate these issues.

Future Research Directions

Future research should focus on several key areas to address the chemical impacts of waste management. First, chemical impact studies should delve into the reactions occurring during waste decomposition and combustion, identifying specific pollutants such as dioxins, furans, and heavy metals and their health effects. Additionally, developing cleaner technologies is crucial; this includes researching advanced waste-to-energy systems, controlled incineration methods, and hazardous waste neutralization techniques. Monitoring and mitigation strategies must also be refined to track pollutants in real time, evaluating their environmental and health impacts. Assessing the impact of policy changes on chemical pollution and health outcomes is essential for refining regulations and practices. Public health studies should investigate chronic conditions related to waste-derived chemicals and support targeted interventions. Finally, enhancing community education can improve waste management practices and reduce chemical risks. Addressing these research areas will help Bangladesh develop effective waste management strategies, improving public health and environmental sustainability.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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