Advancements and Challenges in Municipal Solid Waste Management: A Comprehensive Analysis of Disposal Methods and Their Environmental Impacts

Weitao Li[1*]

[1]New York University Tandon School of Engineering, New York City, the United States

Abstract. Under such growths of global population and development of urbanization, Municipal Solid Waste (MSW) generation has increased drastically and become a vital issue all over the world. Efficient MSW management and recovery of MSW play a critical role in reducing its negative impacts on the environment and human health. The review has illustrated a general perspective of MSW background and current issues related to the MSW management by explaining some examples of the negative impacts from different methods of disposing MSW. The paper presents an in-depth analysis the characteristics of MSW and methods for classifying MSW, as well as the advantages and limitations of physical, chemical, and biological disposal techniques, such as landfill, hazardous waste disposal, chemical treatment, immobilization, anaerobic digestion, and composting. Furthermore, the review highlights the importance of an integrated waste management approach that combines these methods with waste reduction, reuse, and recycling strategies to minimize the environmental and public health impacts of waste disposal.

1 Introduction

With the continuous increase of population density and the development of urban and rural construction, the rapid urbanization process exacerbates the MSW crisis, as cities struggle to keep up with the escalating waste streams. As the world's population continues to grow, reaching an estimated 9.8 billion by 2050, the demand for food, housing, transportation, and other basic services are expected to increase. As a result, there will be a considerable rise in MSW generation, as the rapid growth of population, industrialization, and urbanization can effectively cause a higher rate of MSW generation. MSW generation will also become an inevitable consequence of urbanization and population growth, presenting a critical environmental and public health concern all over the world. MSW mismanagement due to population growth and urbanization has significant impacts on both the environment and public health. The improper disposal of MSW can cause land pollution, which generates hazardous pollutants to contaminate soil and affects agricultural development. Water pollution caused by insufficient landfill management can seriously destroy aquatic habitats and lead to health risks for people. Greenhouse gas emissions from waste disposal activities should be addressed because the emissions can reach up to over 700 kg per tonne of MSW directly from the disposal process [1]. The annual global generation of MSW has been estimated as 2.24 billion tonnes, which accounts for each person each day producing 0.79 kg MSW [2]. Since the negative impact of MSW, appropriate and sustainable MSW management strategies are necessary for environmental governance and human health.

MSW management consists of several stages, namely waste generation, collection, transportation, sorting, recycling, treatment and disposal. The effectiveness of each stage plays a key role in the whole management system. Physical, chemical, and biological disposal methods play an important role in municipal solid waste management and are a major source of environmental impact. Physical methods such as landfills are widely used, but also pose considerable environmental challenges, including groundwater pollution, greenhouse gas emissions, habitat destruction and space occupation. Chemical methods such as incineration have the potential to generate energy from the process of disposing of waste. However, they also produce harmful emissions and byproducts, such as fly ash, that threatens the environment and human respiratory systems. Biological methods such as composting and anaerobic digestion are considered relatively environmentally friendly options, converting organic waste into valuable products such as compost and biogas. This paper aims at provide a comprehensive understanding of the challenges, opportunities, and environmental impacts of various disposal methods, offering valuable insights for future sustainable development within disposal of MSW.

* Corresponding author: wl2535@nyu.edu

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2 MSW classification

MSW includes household waste, commercial waste, discarded building materials, hazardous waste, electronic waste, and waste from various institutions. It mainly comes from the solid waste produced in the daily life of urban residents or in the activities providing services for urban daily life. Urban households, urban businesses, tourism, services, transportation, and industrial enterprises account for the majority of urban solid waste production. The composition of municipal solid waste is heavily dependent on the source and location. The most common types of municipal solid waste are household waste, commercial waste, industrial waste, construction and demolition waste, and biomedical waste.

2.1 MSW characteristics and types

Household waste is generated by urban residents, which could be non-hazardous waste and hazardous waste. Non-hazardous waste includes food waste, kitchen waste, used paper or towels, and plastic material products like water bottles, which could be recycled or composted by proper disposal. Hazardous waste includes batteries, pesticides and solid products that might cause pollution or toxic elements in the environment [3]. Groundwater can be affected if household waste remains in the ground without any correct management. Also, household waste can have potential to cause human uncomfortable symptoms like headache, issues of nervous system, etc. Commercial and industrial wastes are the byproducts of production or business operations which are not-for-profit solid wastes. However, commercial and industrial waste can hold the potential for recycling, with recyclable materials such as paper, cardboard, and plastic often present in significant amounts. According to the U.S. Environmental Protection Agency, paper and paperboard products make up the largest portion of the municipal solid waste stream in the United States, accounting for approximately 25% of the total. Much of this paper waste comes from commercial and industrial sources, such as offices, retail stores, and warehouses. Construction and demolition waste (CDW) refers to the waste produced from land excavation or formation, civil and building construction, site preparation, deconstruction, maintenance of transportation infrastructure, and retrofitting of existing structures [4]. CDW typically consists of a mix of heavy, bulky materials which could be hazardous and non-hazardous types. The hazardous materials contain asbestos, lead, and mercury. According to the World Bank, CDW has accounted for about 30% of the total solid waste generated in the world until 2018 [5]. Biomedical wastes are solid wastes generated during medical diagnosis, treatment, and immunization from human or animal sources. Approximately 75% and 90% of BMW is non-hazardous or general medical waste. However, the rest of the 10% to 25% is considered as hazardous waste which causes serious environmental and public health impacts [6].

3 Importance of MSW management

The world population will increase to over 8 billion by 2023, and each person could produce about 4.9 pounds of solid waste per day in 2018 [7]. As the development of urbanization, industrialization, economy, transportation, and general institutions, the issue of municipal solid waste should be addressed and concerned to help catch up with the social developed paces.The Effective management of municipal solid waste could result in less pollution and fewer hazardous impacts on public health and environment. Also, the effective management of MSW can benefit from recycling of MSW. General management of municipal solid waste is concluded in six organized steps: waste generation, waste source treatment, collection, transportation, treatment and conversion, and disposal [8].

3.1 General management

Waste generation refers to the process of producing solid waste. Waste source treatment is a stage of solid waste management that involves reducing the amount of waste generated at its source, before it enters the waste management system. This can be achieved through various waste reduction techniques, including waste reduction, reuse, recycling, and composting. Waste reduction can be reducing food waste in daily meals. People should bring reusable bags during shopping or buying recycling necessities for daily life. Composting can involve breaking down organic waste materials such as food scraps and yard waste into a nutrient-rich soil amendment, which is sustainable for the environment. Waste collection and transportation depend on the type and volume of waste being generated. They can have a significant impact on the cost and environmental impact of waste management, because during the process of waste collection and transportation, the solid waste might have long exposure to the air and lead to unpredictable harms to the public health or environment. Treatment and conversion are the vital processing waste to reduce its volume, recover valuable resources, and prepare the waste for next disposal. Treatment methods can include physical, chemical, and biological processes, and conversion methods can have incineration, pyrolysis, and gasification. Waste disposal is the final stage of waste management for the waste that cannot be reduced, reused or recycled. Waste disposal covers the approaches mentioned in treatment and conversion steps.

4 Physical methods design

Landfill is the primary physical and reliable approach for MSW disposal in most of the world because it is a relatively low cost and efficient approach for disposing of large volumes of waste. Landfills are typically located in areas that are not suitable for other uses since landfills can release harmful pollutants into the air and groundwater. The pollutants can be methane, which is one of the major contributors for greenhouse gas emissions and a significant safety hazard when it accumulates in enclosed spaces; leachate, which is a liquid generated in municipal landfill with organic and inorganic pollutants, or heavy metals [9]. Landfill design requirements need to include a compost liner system made of materials such as clay and synthetic liners to prevent leachate from contaminating groundwater. In addition, leachate collection systems are necessarily installed to transport any leachate generated in the landfill to treatment facilities to prevent contamination of nearby water sources. Landfill also equipped with a landfill gas management system to capture and treat methane gas that is produced by the decomposition of organic waste. Landfill covers are used to prevent rainwater from entering the landfill and to control odors [10].

4.1 Landfill operation

Landfill operation requires waste compaction to reduce the amount of space occupied by the waste and minimize the amount of air present, which can contribute to the production of methane gas. Landfill gas management is also critical to capture and treat methane gas to prevent it from being released into the atmosphere and contributing to climate change [11]. Landfill has been the major approach to solve the large amount of MSW in China for years. Within ten years from 2009 to 2018, the quantity of disposed MSW has increased from 112.32 million tons per year to 225.65 million tons per year [12]. Landfill has played an important role in disposing of MSW and is responsible for over half of the MSW per year, which is 117.06 million tons per year. Most of the landfill sites in China are positioned in the southeast area densely populated areas with advanced industrialization, and they have the ability to generate electricity by using gas emitted from the landfill through conversion equipment. Almost half of the gas produced in the process of landfill is methane, after converting, each ton of MSW can produce 65 Nm^3 of methane. There is research recording that 3.3×10^9 Nm^3 landfill gas can have potential to generate energy sources like electric power (7.39×10^9 kWh) and fossil gas (1.7×10^9 Nm^3) [12].

5 Chemical waste disposal method

Municipal solid waste incineration (MSWI) approach could reduce relative volume occupied by solid waste compared to landfill. However, the approach of MSWI produces secondary pollutants called fly ash [13]. MSWI fly ash is a byproduct of the incineration of municipal solid waste and is considered hazardous due to the presence of heavy metals, dioxins, and other toxic substances [14]. The disposal of MSWI fly ash typically involves identifying its hazardous components, segregating it from other waste streams, and treating or disposing of it in designated facilities, such as secure landfills or specialized treatment plants. The composition of fly ash may vary, depending on the composition of the waste being incinerated and the operating conditions of the incinerator. In general, however, fly ash usually contains a mixture of inorganic compounds, such as silicon dioxide, alumina, iron oxide, calcium oxide and magnesium oxide. It can also contain trace amounts of heavy metals and other contaminants.

5.1 Chemical treatment

Chemical treatment is a disposal method that aims to detoxify MSWI fly ash by neutralizing, reducing, or removing its hazardous components. This approach involves using chemical reactions or processes to convert the harmful substances in the fly ash into less toxic or non-hazardous compounds. Common chemical treatment methods for MSWI fly ash include acid washing, and alkaline washing. Acid washing uses acidic solutions to dissolve and remove heavy metals from the fly ash, while alkaline washing uses alkaline solutions to neutralize acidic components and reduce the leachability of heavy metals [15]. One relevant experiment has dissolved 0.2 mol/L hydrochloric acid and 0.06 mol/L sulfuric acid in water as mixtures to treat fly ash and analyze the leaching value of the obtained heavy metals. It was found that under the solid-liquid ratio of 20:1, the leaching value of lead and zinc decreased by 99% and 96%, respectively [16].

5.2 Chemical immobilization

Chemical solidification/stabilization (S/S) is a disposal method that focuses on stabilizing and containing the hazardous components of MSWI fly ash to prevent their release into the environment. The S/S process typically involves three steps: mixing the waste material with the binding agent, curing the mixture to allow the binding agent to react with the waste material, and testing the resulting material to ensure that it meets regulatory standards for disposal. In the case of the novel alternative binders described in the article, the binding agents are derived from cementitious waste and are shown to effectively immobilize heavy metals and other contaminants in MSWI fly ash. Dehydrated cement waste (DCW) was experimentally used as an alternative adhesive to fix hazardous municipal solid waste incineration fly ash (IFA). DCW is produced by dehydration of cement-based waste at different temperatures (200, 500, and 800 degrees Celsius). By mixing DCW with IFA, more than 98% of the lead element was immobilized and prevented from leaking out of the mixture [17]. Chemical solidification has several advantages over other waste management techniques, including its ability to immobilize contaminants and create a stable, solid material that can be safely transported and stored. However, it can also be more expensive than other waste management techniques.

6 Biological waste disposal methods

The population growth in the urban areas can significantly increase the amount of solid waste from household, commercial, and industrial divisions. These large amounts of MSW can affect the ecology systems of countries and bring harm to the environment and public health if its disposal is improper or ignored. Landfill, as mentioned above, is the primary and low-cost approach to manage MSW throughout the world. MSWI, as a chemical perspective method, can reduce the spaces required for disposing municipal solid waste compared to the method of landfill. However, MSWI can produce hazardous byproducts such as fly ash. The biological treatment for MSW is considered as a sustainable approach because biotreatment can not only reduce solid waste volume during the disposal process, but also has generation of biomethane energy sources. Biotreatment generally has two types, which are anaerobic and aerobic methods.

6.1 Anaerobic and aerobic digestion

Anaerobic digestion refers to the process of microorganisms breakdown organic waste in the non-oxygen supplied environment [18]. Anaerobic digestion approach can be illustrated by wet and dry anaerobic processes. Wet anaerobic process involves disposing of the solid wastes which are moisture, while dry anaerobic process involves disposing of dry solid waste [19]. In the first stage, hydrolysis, large organic molecules in MSW are broken down into smaller compounds such as sugars, amino acids, and fatty acids. In the second stage, acidogenesis, the smaller compounds are further broken down into organic acids such as acetic acid and butyric acid. In the third stage, acetogenesis, the organic acids are converted into acetate, hydrogen, and carbon dioxide. Finally, in the fourth stage, methanogenesis, methane-producing microorganisms convert the acetate, hydrogen, and carbon dioxide into biogas, a mixture of methane and carbon dioxide . The maximum methane yield depends on parameters in the anaerobic process including feedstock composition, organic load rate, hydraulic retention time, temperature, and pH. Experiments have shown that biogas and methane of 0.535 m^3/kg and 0.350 m^3/kg can be produced by anaerobic digestion process at room temperature of 48 to 52 degrees Celsius, organic load rate of 4.6 kg/m^3 day and MSW mass of 148 tons per day [20]. Aerobic process involves the use of oxygen to break down organic MSW. In an aerobic decomposition system, as the aerobic bacteria consume the organic waste in MSW, they produce carbon dioxide, water, and heat. The final production of the aerobic process is the nutrient-rich compost which can be used for agriculture [18].

7 Conclusion

In general, the effective management of MSW is of paramount importance because the ignorance of management can cause significant harm to the environment and public health. The public awareness of MSW generation and future sustainable disposal practices has become increasingly evident. This paper has presented a comprehensive overview of MSW current situation within the development of population and urbanization, MSW classification and essential approaches for MSW disposal, including physical treatment (landfill), chemical treatment (incineration), biological treatment (anaerobic and aerobic digestion). These methods are the most commonly employed though each of them has individual benefits and limitations, necessitating a thoughtful and integrated method to MSW management with consideration in waste components, and available resources. The benefit of using those methods rationally could help produce the impact on climate change and hazardous pollutants or emissions. Landfill and anaerobic digestion processes can not only treat MSW generation, but also convert the gas emitted in the process of collecting and treating MSW into other forms of energy sources. Addressing the complex issue of MSW still requires further promotion of MSW management and concert effort from stakeholders, including global organizations, industry, and civil society.

References

1. R. L. Verma and G. Borongan, Urban Sci., **6**, 78 (2022)
2. World Bank Group, https://www.worldbank.org/en/topic/urbandevelopment/brief/solid-waste-management, accessed on Apr. 18, 2023
3. Household Hazardous Waste (HHW) | US EPA, US EPA, https://www.epa.gov/hw/household-hazardous-waste-hhw, accessed on Apr. 18, 2023.
4. H. Yuan and L. Shen, Waste Manage., **31**, 670 (2011)
5. What a Waste. https://datatopics.worldbank.org/what-a-waste/, accessed Apr. 18, 2023
6. M. R. Capoor and K. Bhowmik, Indian J. Med. Microbiol., **35**, 157 (2017)
7. National Overview: Facts and Figures on Materials, Wastes and Recycling | US EPA, US EPA, Dec. 03, 2022. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials, accessed on Apr. 18, 2023.
8. G. Tchobanoglous,AccessEngineering | McGraw-Hill Education - Access Engineering, (2002)
9. S. M. Raghab, A. Meguid, and H. A. Hegazi, HBRC J., **9**, 187 (2013)
10. Municipal Solid Waste Landfills | US EPA, US EPA, https://www.epa.gov/landfills/municipal-solid-waste-landfills#whatis, accessed on Apr. 18, 2023
11. Z. Duan, L. S. Jensen, and P. Kjeldsen,Waste Manage., **119**, 39 (2021)
12. S. A. Khan, R. Anjum, S. A. Raza, N. A. Bazai, and M. Ihtisham, Chemosphere, **288**, 132403 (2022)
13. Y. Xue and X. Liu, Chem. Eng. J., **420**, 130349 (2021)

14. D. Zou, Y. Chi, C. Fu, J. Dong, F. Wang, and M. Ni, J. Hazardous Mater., **248**, 177 (2013)
15. A. Ferraro, I. Farina, M. Race, F. Colangelo, R. Cioffi, and M. Fabbricino,Rev. Environ. Sci. Bio/Tech., **18**, 453 (2019)
16. Y. Cao, J. Luo, and S. Sun, J. Fuel Chem. Tech., **49**, 1208 (2021)
17. P. Tang, W. Chen, D. Xuan, H. Cheng, C. S. Poon, and K.-H. Kim,J. Hazardous Mater., **393**, 122386 (2020)
18. A. Saravanan, P. S. Kumar, T. C. Nhung, B. Ramesh, S. Srinivasan, and G. Rangasamy, Chemosphere, **309**, 136630 (2022)
19. E. Angelonidi and S. M. Smith, Water Environ. J., **29**, 549 (2015)
20. A. Kumar and S. R. Samadder, Energy, **197**, 117253, (2020)