

SUSTAINABLE PATHWAYS FOR MUNICIPAL SOLID WASTE MANAGEMENT TECHNIQUES IN KHULNA CITY, BANGLADESH

Md Habibullah^{*1}, Md Mojeb Ali², Shaikh Azhar Mahmud³, Md. Abul Khair⁴, and Dr. Md. Mafizur Rahman⁵

¹ Undergraduate Student, Department of Civil Engineering, Gopanganj Science and Technology University, Bangladesh, e-mail: mdhabibullah.19ce@gmail.com

² Postgraduate Student, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Bangladesh, e-mail: mdmojebali2@gmail.com

³ Undergraduate Student, Department of Civil Engineering, Gopanganj Science and Technology University, Bangladesh, e-mail: azharmahmud144@gmail.com

⁴ Undergraduate Student, Department of Civil Engineering, Gopanganj Science and Technology University, Bangladesh, e-mail: abulkhair.19ce002@gstu.edu.bd

⁵ Professor, Department of Civil Engineering, Bangladesh University of Engineering and Technology, Bangladesh, e-mail: mafizur@gmail.com

***Corresponding Author**

ABSTRACT

Due to the rapid urbanization, population growth, and industrial and economic development, solid waste management (SWM) has become a major concern in both developing and developed countries. Effective SWM is important for protecting public health, conserving resources, and minimizing environmental degradation. The approaches to SWM should be compatible with the nature of a given society, and Khulna City is not an exception in this regard. Khulna is the third largest city in Bangladesh and generates about 1400 tons of waste daily, but Khulna City Corporation (KCC) picks up nearly 800 to 900 tons of waste, and the rest remains uncollected. This paper explores the current generation, collection, and transportation system of solid waste and existing management techniques. The aim of this study is to identify the key issues contributing to inefficient waste handling and find out the alternate solutions to minimize waste generation. Among these, landfilling is a widely used technique in many municipalities around the world. Landfill sites serve as ecological reactors, facilitating the physical, chemical, and biological transformation of waste. Most of the newest efforts are aimed at reaching "Zero Waste" or "Zero Landfilling", which is very costly for countries with weak economies. To move forward with sustainable solid waste management in developing Asian countries, it is important to deal with these problems with strategies that are both cost-effective and tailored to the situation.

Keywords: *Solid waste management (SWM), Incineration, Sustainability, Recycling, Waste-to-Energy.*

1. INTRODUCTION

All over the world, solid waste management (SWM) is a big problem for the economy and the environment (Demirbas, 2011). It would be a big help to make new materials as a substitute of using fossil fuels if we could recycle more valuable things from waste (Tonini & Astrup, 2012). We release a lot of greenhouse gases that trap heat when we make, use, and throw things away. These emissions come from a lot of diverse places. For instance, when new materials are taken out of the ground and made, carbon dioxide is released. When organic waste breaks down in landfills, methane is released. As technology has become improved and the population has grown up, the amount of solid waste we make has gone up. People throw away things in a lot of places, like small homes and big companies. Cities have a lot of people and use a lot of resources, which means they also make a lot of waste. People who live in cities throw away two to three times more solid waste than people who live in the country (Bari et al., 2012).

Urbanization is happening so quickly that the rapid growth of MSW has become a big problem for keeping the planet clean. The world makes 2.01 billion metric tonnes of municipal solid waste every year. It is expected that the world's yearly production of Municipal Solid Waste (MSW) will reach 2.59 billion tonnes by 2030 and 3.40 billion tonnes by 2050 (Kaza et al., 2018). The most cautious estimate says that 33% of it is not being done in a way that is good for the environment. The percentage is even higher in countries that are still developing or have not fully developed yet (Jerin et al., 2022). The amount of MSW made each day varies by place and level of economic development, from 0.11 kg to 4.54 kg. It is anticipated that waste will increase by 19% in developed countries and 40% in developing countries (Roy et al., 2022).

Waste production in Khulna increases with the city's population growth. Solid waste management is made very difficult by this. By appropriately managing solid waste, the Khulna City Corporation (KCC) can ensure that the city is hygienic and safe. The volume and kind of Waste, principally domestic waste, must be considered to establish a system that will endure (Ogwueleka, 2013). Important information about the composition of debris will be gleaned from this study, which will make it easier to create specialized collection, transportation, and disposal plans (Abir et al., 2023). Reducing the damage that solid waste does to the environment requires effective management. By investigative what constitutes municipal waste, we may recognize hazardous substances and waste that nature cannot decompose. By doing this, we can dispose of the waste without contaminating the land, water, or air (Abir et al., 2023).

Also, the rising amount of solid waste puts a lot of pressure on local governments' budgets for dealing with it (Bundhoo, 2017). Not properly disposing of solid waste can affect the environment a lot. For instance, methane from organic waste can make the Earth warmer and change the weather. It can also make fires more likely, leachate can contaminate groundwater, and it can spread diseases that insects carry. It is hard to get rid of solid waste in a good way all over the world, and these environmental hazards make it even harder (Bundhoo, 2017) (Guerrero & Hogland, 2013).

Picking up MSW is part of managing waste. In advanced countries, there are official ways to pick up trash, but in developing and underdeveloped countries, most of the time, they use unofficial methods (Roy et al., 2022). Countries with high incomes pick up 96% of the MSW, while countries with low incomes only pick up 39% (Iyamu et al., 2020). In developing countries, the technologies and tackles used to pick up waste are old and not well-maintained, and break down (Faccio et al, 2011). According to this source, these things make up 80–95% of the total budget for managing MSW in developing countries. In developed countries (Roy et al., 2022), the percentage charge is less than 10% because of good planning and money management.

This study seeks to do an exhaustive analysis of the existing solid waste management practices in Khulna City. The study will look at how waste is generated, what it is made of, and how it is collected. The objective is to find out how these things impact how effectively waste management

programs operate. The main objective is to find practical, economical solutions that work for Khulna municipal and other developing nations with cities like it, so that waste management lasts and is sustainable.

2. METHODOLOGY

2.1 Selection of Study Area

Khulna is the third largest city in Bangladesh, and it has a population of about 1.3 million. The city cooperation consists of 31 wards and covers an area of 14.30 square miles. About 15.5% of families in Khulna are rich, and 23.6% are poor. The KCC has a literacy rate of 73.6% (KCC, 2023). In Khulna city, 1000 tonnes of solid waste are made every day, typically from food and vegetable waste. The main places where this waste comes from are residential areas (KCC, 2023).

The study looked at the major residential areas of Khulna City Corporation (KCC) (between 21.38 N and 23.1 N Latitude and 88.58 E longitude), which are representative of the city's overall waste management conditions.. The study also includes the Rajbandh Landfill (Latitude: 22°47'43.17", Longitude: 89°29'58.35") which serves as the primary waste dumping station for the city.

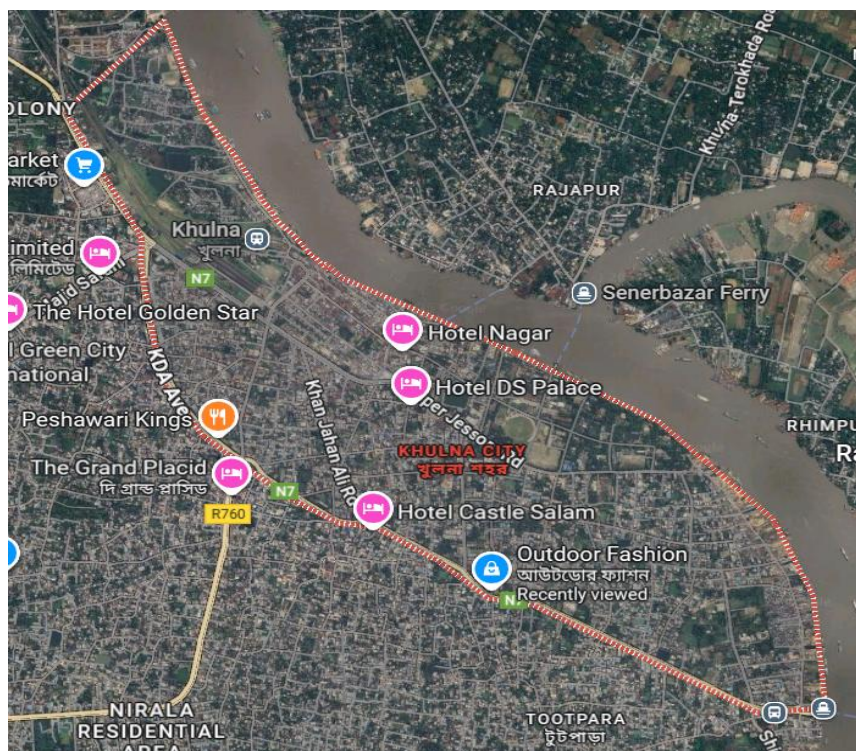


Figure 1: Map of the Study area, KCC (Source: Google Maps).

The Rupsha and Bhairab rivers run through the city. Most of the factories are near the rivers, which is where industrial waste goes. Because of poor management system, these rivers also get municipal solid waste, which is bad for people's health, the environment, and the ecosystem. According to the KCC Ordinance 1984, the KCC oversees picking up, moving, and getting rid of solid waste. But they could not do it because they did not have enough money and had other issues.

2.2 Waste Generation, Collection and Transportation Systems

Municipal areas have many different places where solid waste comes from. People who live in homes, businesses, and public and private institutions all make waste. According to the law, solid waste is

defined in terms of certain categories in many Asian countries. But the municipalities must deal with everything that people throw away. This paper discusses solid waste managed by municipalities. Municipal solid waste (MSW) is all the waste and non-hazardous waste that comes from homes, businesses, and institutions, as well as street sweepings and construction debris (Shekdar, 2009). The major sources, their typical generators, and types of waste are shown in Table 1.

Table 1: Sources and types of municipal solid waste (Sources: Global Waste Management Outlook 2024)

Sources	Typical waste generators	Types of solid waste
Residential	Single and multifamily dwellings	Paper, plastics, glass, textiles, food scraps, metals, cardboard, ashes, electronics, tires, batteries, oil, and household hazardous wastes.
Commercial	Markets, restaurants, hotels, stores, and office buildings.	Glass, food waste, metals, plastic, cardboard, hazardous waste, wood, paper, and special waste.
Institutional	Hospitals, schools, prisons, and government centres.	Metals, glass, food scraps, plastic, wood, cardboard, paper, dangerous wastes, and special wastes.
Municipal services	Beaches, parks, street cleaning, recreational areas, and landscaping.	Trash from parks, beaches, and recreational spots, along with tree trimmings, landscape waste, and street sweepings.

Khulna City's organized system for dealing with municipal waste includes both public and private efforts. People in the city are responsible for taking their household waste to roadside bins that the city corporation provides. First, they store their waste until there is enough to fill a bin. After the trash is put in these bins, the city corporation oversees taking it to the final disposal site. In some places, primary collectors who work for NGOs and Community-Based Organizations (CBOs) also pick up waste every day. These collectors use rickshaw vans to pick up trash from homes (Figure 3) and take it to certain transfer points (Figure 4). After that, the city corporation finishes the secondary collection phase by sending big trucks to pick up the trash from these places. The city corporation oversees the whole process to make sure that the trash is thrown at the ultimate disposal point (Figure 5) properly (Ahsan et al., 2009). The Khulna City Corporation (KCC) works with about 16 NGOs and 2 CBOs right now to handle solid waste. Their main job is to pick up trash from people's homes. The city corporation, NGOs, and CBOs work together to make waste management in Khulna more efficient. This makes sure that waste is handled properly from the home to the place where it is finally thrown away. The daily waste composition in Khulna City Corporation (KCC) are shown in Figure 2 and it also varies with different income groups shown in Figure 6.

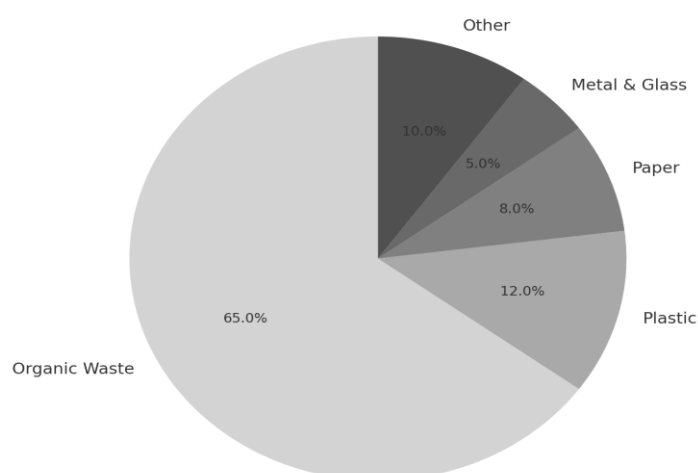


Figure 2: Daily Waste Composition in Khulna City (Source: KCC)



Figure 3: Waste Pickup (Shibbari More, Khulna)



Figure 4: Transfer Point (Circuit House, Khulna)



Figure 5: Ultimate Disposal Point (Rajbandh Landfill, Khulna)

Waste Composition by Income Group in KCC (Monochrome Theme)

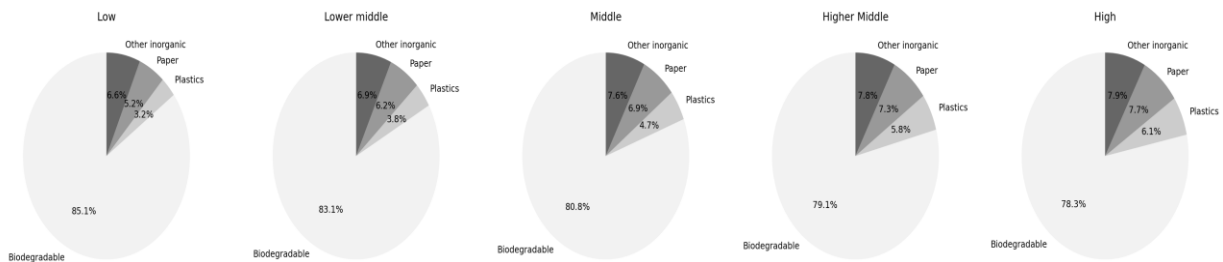


Figure 6: Waste composition by income groups in KCC (Source: KCC)

2.3 Existing Solid Waste Management Techniques

2.3.1 Open Burning

In many parts of the world, especially in developing countries where waste management systems aren't very good, open burning of solid waste is a common but very bad thing to do as shown in Figure 7. Controlled incineration is not the same as open burning because it happens in open areas, like cities or near landfills, and no one oversees the waste burning. This way is cheap and quick, but it could be bad for your health and the environment. When you burn things outside, they let out smoke that has harmful chemicals like carbon monoxide, particulate matter, and poisonous chemicals like dioxins and furans. These can make it tough to breathe, cause heart disease, and even cancer (Velis, 2021). Open burning releases a lot of carbon dioxide, which is bad for people who live nearby and for the climate around the world. Open burning often comprises burning diverse waste, such as plastics and other dangerous ingredients. This makes it much more dangerous to people and the environment than more controlled ways of getting rid of waste. So, even though open burning might seem like an easy way to get rid of trash, its long-term effects make it an unsafe and unsustainable practice that needs to be stopped right away and replaced with something else (Kundariya et al., 2021).



Figure 7: Open Burning (Hogladanga, Khulna)

2.3.2 Open Dumping

In poor nations, visitors to the country confront a lot of problems, including the smoking from burning trash, which covers portions of housing areas and makes life worse for the people who live there. People are affected by the smell of waste that is rotting and the smoke from burning trash. During the rainy season, these annoyances become worse since the region is full with flies and bugs, which makes the atmosphere dirtier and spreads illnesses. The principal problems found include open dumping in unrestrained areas, open burning of waste fractions, and poor management of leachate from final disposal sites (Kundariya et al., 2021). Things are worse in slums, where there are more difficulties with crowded people, traffic, and pollution of the air and water. In these situations, people often throw things out in open areas near bodies of water without any oversight, which might cause health problems (Kundariya et al., 2021). Open-air ultimate disposal has a lot of bad effects on the environment, including as bad smells, air pollution, greenhouse gas (GHG) emissions, disease-carrying insects, and pollution of surface and groundwater. During the rainy season, the neighborhood is full with flies and other bugs, which makes the problems much worse. Water bodies are polluted by runoff from the dump site that contains dissolved toxins, while the land and groundwater are polluted by leachate. Also, the wells around the site were contaminated with a lot of faecal and total coliform, which is bad for the ecosystem. People that live near the dumpsite use well water for a lot of different things, even though it has a lot of coliforms since it is so close to the dump site (Ferronato & Torretta, (2019). The leachate from open dump sites includes a lot of ammonia, chloride, organic carbons, heavy metals, and a lot of fluoride, chloride, biological oxygen demand (BOD), ammonium–nitrogen, and chemical oxygen demand (COD) (Torretta et al., 2017). According to reports, the leachate produced greater levels of Cr, Cd, and Mn in the groundwater, which had a bad impact on the health of the people and the environment (Ferronato & Torretta., 2019). Figure 8 shows open dumping sites as ultimate disposal point.



Figure 8: Open Dumping (Rajbandh Landfill, Khulna)

3. ALTERNATE SOLUTIONS

3.1 Waste To Energy (WTE)

Thermochemical approaches like incineration, pyrolysis, gasification, and hydrothermal liquefaction can turn MSW into energy (Kundariya et al., 2021). Thermochemical processes are getting more consideration because they are more efficient, produce less waste, and work better with a wider range of feedstocks (wet and dry).

3.1.1 Incineration

Incineration is the progression of burning waste with a lot of oxygen at temperatures between 800 and 1200°C (Nanda & Berruti, 2021). Burning, disintegration, and drying are the three primary processes. Eradicating the moisture from the trash is the first step. Gases such as water vapor, CO₂, CO, H₂, and CH₄ are then released when the organic matter decomposes. Finally, the remaining char and these gases are burnt to provide thermal energy. The carbon and hydrogen in the waste are transformed to carbon dioxide and water when they burn (Shah et al., 2022). Incineration is a well-known way to get

rid of trash that works best for trash with high calorific values. It cuts down on the volume of waste by 70 to 90%. This process turns the energy that is made into electricity. There are three steps: (1) burning the MSW with air at 700–1000 °C, (2) using the hot gases from the scorching to get back heat and electricity, and (3) keeping releases under control. Incineration helps obtain energy back from waste, but it also makes greenhouse gases like CO₂ and NO_x (Ouda et al, 2017).

3.1.2 Pyrolysis

Pyrolysis is a way to break down municipal solid waste (MSW) by heating it to 300–1000°C without any air. It turns into bio-oil, syngas, and char. Many people believe that it is one of the best waste-to-energy (WTE) technologies because it can turn trash into useful fuels and materials while polluting less (Beyene et al., 2018). The quality and yield of the products depend on several things, such as the temperature, the rate of heating, the amount of time the feedstock stays in the system, the size of the particles, and the composition of the feedstock. Maximum bio-oil yield is typically achieved at 500–600°C with a residence time of 5–20 minutes. Under these conditions, free radicals, and hydrogen donors, which are intermediate by-products, help make bio (Varjani et al., 2022).

3.1.3 Gasification

Gasification is another advanced thermochemical waste-to-energy (WTE) method. It heats the feedstock to 500–900°C with a controlled amount of oxygen, steam, or air to turn municipal solid waste (MSW) into syngas, which is a mix of CO, H₂, CH₄, and small amounts of other hydrocarbons. The progression has four steps: drying, pyrolysis, oxidation, and reduction. It contains both endothermic and exothermic steps. Gasification might be a procedure to make energy that lasts because it not only gets energy back but also makes hydrogen, which is a clean fuel with a high heating value of 141.7 MJ/kg (Nanda & Berruti., 2021). Different reactions occur at different temperatures, and these reactions create compounds like light hydrocarbons, phenolics, and aromatics. Hydrothermal gasification works better and is better for the environment even at lower temperatures. This is because it breaks down feedstock faster, turns more carbon into hydrogen, and makes less tar and char than traditional gasification (Varjani et al., 2022).

3.1.4 Hydrothermal Liquefaction

Using subcritical or supercritical water as a solvent, hydrothermal liquefaction (HTL) turns wet biomass into biocrude oil at temperatures between 250 to 375°C and pressures between 5 to 25 MPa. It saves electricity since it does not need to be dried, which makes it operate very well. HTL produces biocrude oil as well as beneficial byproducts such as polyurethane foams, adhesives, resins, and biopolymers. Yield is affected by temperature, pressure, how long the material stays there, and how much solid it contains (Varjani et al., 2022). The best pressure, residence time, temperature, and solid content for making biocrude are usually 330 to 350°C, 10 to 15 MPa, 50 to 90 minutes, and 10 to 15%, respectively. Reactions such as thermal degradation, hydrolysis, hydrogenation, and decarboxylation convert complex organic molecules into fuel-rich, simpler chemicals. Because of this, HTL is a potentially environmentally friendly method of producing liquid fuel from MSW and other biomass sources (Alper et al., 2020).

3.2 3R Principles

Waste management starts with making less waste and sorting out things that could be recycled at the source. This process makes the materials better for reuse, such as organic waste for composting or anaerobic digestion. Whenever possible, items that can't be reduced should be used again. If reuse is not possible, materials, especially metals and paper, should be recycled. If waste cannot be recycled, it should be improved, usually through biological decomposition, or burnt or buried (World bank, 2005).

The most common ways to eliminate of trash are to reduce, reuse, and especially recycle (Daniel, 2003). Policies that include cutting down on waste, reusing it, recycling it, and composting it are often called "zero waste" strategies because they want to have no disposals and no negative effects on the

environment. It is challenging to reach true zero waste, but it is possible. Long-term use of more than one waste management strategy can help reduce waste in a way that is advantageous for the environment (Lead et al., 2005).

3.2.1 Reduce

The first step to good waste management is to stop waste from being made in the first place by cutting down on it at its source. This is in line with the principle of prevention, which is also called the "avoidance of waste". Limiting the use of raw materials is one of the best ways to cut down on the amount of solid waste that needs to be thrown away (Sabir, 2006). For instance, cutting down on packaging can cut down on both the amount of waste produced and the number of resources used. You can also cut down on waste by using fewer plastic bags, disposable plates, cups, and utensils, and by choosing reusable options whenever you can (Samiha, 2013).

3.2.2 Reuse

The next best thing to do is to use them again if you can't stop wasting them. You may mend items, sell them, or give them to community organizations or charities for use again. This helps cut down on the quantity of rubbish. Reusing is usually better than recycling since the item does not have to go through the recycling process again. People, cultures, and the environment may all benefit from well-planned reuse initiatives (Samiha, 2013). In many affluent nations, including Japan, Sweden, Belgium, and Denmark, more than 90% of solid trash is repurposed. In impoverished nations, reusing things is also highly significant. People had to pay for plastic bags in China in 2008. People were more inclined to utilize reusable bags after this. You may get these reusable solutions at grocery stores. They have been proved to help people use fewer plastic bags. Many underdeveloped nations still use refillable glass bottles in the same way. People bring back empty bottles to grocery shops so they may fill them up again. If they do not, they must pay a deposit charge that is the same as the cost of the bottle. This is a great method to encourage people to utilize items again (Samiha, 2013) (Lino et al., 2012).

Even though fixing things like bikes or furniture can sometimes cost more than buying new ones, many countries now have reuse centers. These centers fix things and sell them for low prices, which makes them last longer. They also give people who have been out of work for a long time or are having trouble finding work a chance to work. "Industry clusters" are being built in rich countries like Japan. The principle of reuse is supported in these clusters because the waste from one industry becomes the resource for another (Lead et al., 2005).

3.2.3 Recycling

Recycling is the process of turning waste materials into new items (open-loop) or the same thing (closed-loop). This helps you retrieve back items that are valuable and produces less trash overall. The informal sector performs most of the recycling in Bangladesh, while official enterprises do relatively little. Families are cutting down on crucial items like paper, plastic, metal, and bottles. After that, street sellers pick them up and carry them to "Vangari Dokans," which are also known as recycling businesses. Second, Figure 9 shows how "Tokai," or slum youngsters, acquire recyclables that are not worth much from bins and public areas. Finally, scavengers uncover additional things at dumping sites, clean them up, sort them, and sell them to industries or wholesalers so they may utilize them again. There are generally three phases to the procedure.

Recycling is vital because it helps us get back things we need and make less rubbish. But in Bangladesh, it largely occurs in larger cities, and the government does not do anything to assist. Some plastics are even delivered to the capital after they have been cleaned and shredded. This shows how valuable the materials that were recovered are (Ahsan et al., 2014).



Figure 9. Collecting Recyclable Materials from Garbage (Rajbandh Landfill, Khulna)

Most of the time, there are three basic processes in the process: collection and sorting, cleaning, and processing, and selling or manufacturing new products. Bangladesh's recycling is still primarily restricted to larger cities like Dhaka, Chattogram, and Khulna. This is because it is crucial to recover resources back and cut down on waste. The government and other groups do not do anything to aid. Some plastics are cleaned and cut up before they are shipped to the capital. This illustrates how much people want and need recycled materials. Bangladesh's recycling industry might be far more efficient and long-lasting if it strengthened official recycling businesses, improved garbage sorting at the source, and gave informal workers training and policy assistance (Matter et al., 2013).

3.3 Landfill Technology

Landfilling is the act of putting trash that can and can't break down into a specific landfill or burial site on land that isn't close to a city. In many countries, landfilling has been a common and profitable way to get rid of trash. It costs less and takes less work to landfill municipal solid waste than to burn it or recycle it. A consolidated landfill can also make money by turning its leachate and landfill gas into energy. Figure 10 shows how a landfill can be used with leachate recycling and turning landfill gas into biogas, which can then be burnt or flared to make heat and power (Nanda & Berruti, 2021).

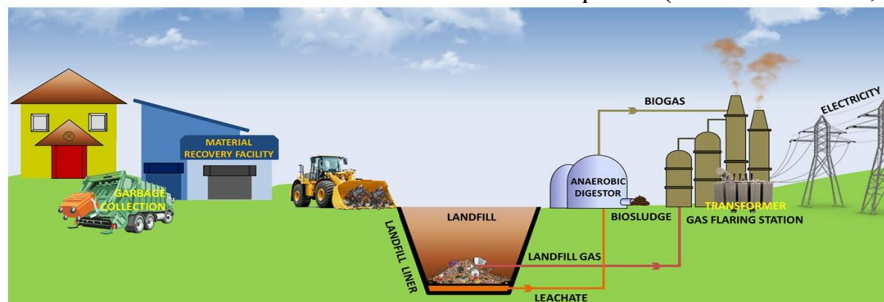


Figure. 10 Consolidated municipal solid waste landfilling system and utilization of leachate and landfill gas for energy generation (Nanda & Berruti, 2021)

In the European Union, there are between 150,000 and 500,000 landfills that are open or closed. These landfills are full of municipal solid waste that comes from Europe (Jones et al., 2013). For example, Europe has more than 150,000 landfills that hold 30 to 50 billion cubic meters of trash from cities (Wagner & Raymond, 2015). In the US, though, the percentage of municipal solid waste that went to landfills dropped from 89% in 1980 to less than 53% in 2014. This was due to better technologies for recycling, composting, burning, and getting energy back. These landfills can convert from "waste storehouses" to "energy powerhouses" that make green energy and other materials if the right technologies are used together.

There are three types of landfills: open dump landfills, semi-controlled landfills, and sanitary landfills. People may see and smell the waste that is dumped away at open dump sites. These kinds of dumps are popular in impoverished nations and draw in scavengers like birds, rats, and bugs. They also put people's health at risk by putting them in contact with microbes. Before being thrown away in semi-controlled landfills, waste is sorted, shredded, and compacted on site. This makes them more organized. Every day, topsoil is put over the trash to stop things like pests and microorganisms from breeding. Still, they do not know how to deal with leachate discharge or landfill gas emissions

(Narayana, 2009). The most sophisticated landfills are sanitary landfills because they contain systems that are designed to handle leachate and landfill gas emissions. To keep odors, pests, and fires to a minimum, trash is sorted, compacted, and covered with dirt on a regular basis. In wealthy nations, these landfills are ubiquitous and are supposed to last a long period. People only dig new sites after they have filled and capped the existing ones. A typical contemporary sanitary landfill contains several distinct pieces, as shown in Figure 11. These sections include the landfill foundation, the bottom liner, the barrier cap, the landfill leachate and gas collecting system, the gas flaring station and layers of municipal solid waste and soil (Nanda & Berruti, 2021).

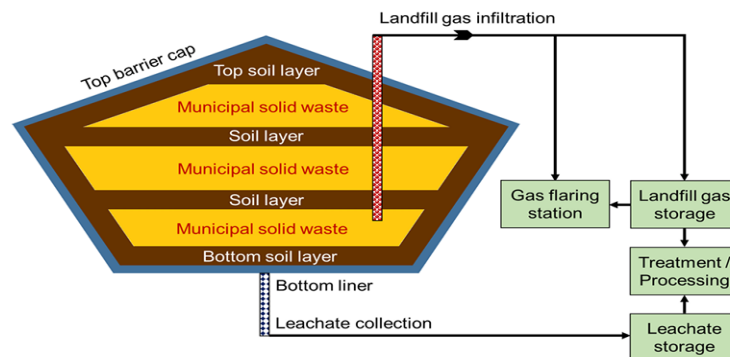


Figure 11. Modern Sanitary Sandfill (Nanda & Berruti, 2021).

4. PROSPECTIVES AND CHALLENGES

Bangladesh is making increasingly MSW, especially in cities and has a lot of chances to make energy from the MSW. The government and other groups can help with this by putting in place the right policies and waste management plans. Local governments could use this supply of MSW as a valuable resource for making energy. The energy that comes directly from solid waste and solid-derived fuels might be a big part of the total energy supply and help solve the energy crisis. The biggest difficulty with this is that people who live in cities, local governments, and government officials don't get along very well. Bangladesh also does not have stringent rules for how to handle MSW. To fix these problems, solid waste requirements to be picked up, controlled, and treated with the right amount of supervision and control. The waste is a good source of renewable energy because it has a higher calorific value for thermal processes. A WTE plant can make power for a circular economy if it is run by the right people.

5. CONCLUSIONS

The study of solid waste management techniques in Khulna City Corporation reveals under significant problems, which is characterized by reliance on primitive techniques like open dumping and burning that pose severe environmental and public health risks. This paper has evaluated several alternate solutions, ranging from advanced Waste-to-Energy (WTE) technologies like incineration, pyrolysis, and gasification, to the foundational principles of the 3Rs (Reduce, Reuse, Recycle), and improved landfill technologies.

Although thermochemical waste-to-energy (WTE) techniques provide the advantages of reducing waste volume and generating energy, their high initial investment and complex technical demands pose significant challenges for implementation, particularly in a developing city like Khulna.

On the contrary, strengthening the 3R framework (Reduce, Reuse, Recycle) and formalizing the already strong informal recycling sector presents a more practical and sustainable solution. This approach is more suitable for cities like Khulna because it not only helps save resources but also cuts down on waste at its source.

To solve Khulna's solid waste problems for good, we need to use more than one technology instead of just one. The most important thing is to focus on reducing waste and recovering materials. This can be done through well-thought-out policies, public awareness campaigns, and the gradual introduction of the right treatment technologies. The ultimate goal is to move from a linear waste disposal system to a circular economy, which will protect the environment and improve the health of the city's residents.

ACKNOWLEDGEMENTS

The authors express their full gratitude to Dr. Md. Mafizur Rahman for active supervision and guidance in doing the research.

REFERENCES

- Abir, T. M., Datta, M., & Saha, S. R. (2023). Assessing the factors influencing effective municipal solid waste management system in Barishal metropolitan areas. *Journal of Geoscience and Environment Protection*, 11(1), 49-66.
- Ahsan, A., Alamgir, M., El-Sergany, M. M., Shams, S., Rowshon, M. K., & Daud, N. N. (2014). Assessment of municipal solid waste management system in a developing country. *Chinese Journal of Engineering*, 2014(1), 561935.
- Ahsan, R., Islam, A. K. M. K., & Shams, S. (2009). *Municipal waste management mechanism for Khulna city: a practice for better environment* (Doctoral dissertation, Khulna University of Engineering and Technology).
- Alper, K., Tekin, K., Karagöz, S., & Ragauskas, A. J. (2020). Sustainable energy and fuels from biomass: a review focusing on hydrothermal biomass processing. *Sustainable Energy & Fuels*, 4(9), 4390-4414.
- Bari, Q. H., Hassan, K. M., & Haque, R. (2012). Scenario of solid waste reuse in Khulna city of Bangladesh. *Waste management*, 32(12), 2526-2534.
- Beyene, H. D., Werkneh, A. A., & Ambaye, T. G. (2018). Current updates on waste to energy (WtE) technologies: a review. *Renewable Energy Focus*, 24, 1-11.
- Bundhoo, Z. M. (2018). Solid waste management in least developed countries: current status and challenges faced. *Journal of Material Cycles and Waste Management*, 20(3), 1867-1877.
- Daniel K. Benjamin, 2003, Eight Great Myths of Recycling, Jane S. Shaw (Ed), PERC Policy Series, Issue Number Ps-28, the Center for Free Market Environmentalism, P: 1- 26, Available Online On PERC's Website: www.perc.org
- Demirbas, A. (2011). Waste management, waste resource facilities and waste conversion processes. *Energy conversion and management*, 52(2), 1280-1287.
- Faccio, M., Persona, A., & Zanin, G. (2011). Waste collection multi objective model with real time traceability data. *Waste management*, 31(12), 2391-2405.
- Ferronato, N., & Torretta, V. (2019). Waste mismanagement in developing countries: A review of global issues. *International journal of environmental research and public health*, 16(6), 1060.
- Guerrero, L. A., Maas, G., & Hogland, W. (2013). Solid waste management challenges for cities in developing countries. *Waste management*, 33(1), 220-232.
- Iyamu, H. O., Anda, M., & Ho, G. (2020). A review of municipal solid waste management in the BRIC and high-income countries: A thematic framework for low-income countries. *Habitat International*, 95, 102097.
- Jerin, D. T., Sara, H. H., Radia, M. A., Hema, P. S., Hasan, S., Urme, S. A., ... & Quayyum, Z. (2022). An overview of progress towards implementation of solid waste management policies in Dhaka, Bangladesh. *Heliyon*, 8(2).
- Jones PT, Geysen D, Tielemans Y, Van Passel S, Pontikes Y, Blanpain B, Quaghebeur M, Hoekstra N (2013) Enhanced landfill mining in view of multiple resource recovery: a critical review. *J Clean Prod* 55:45–55. <https://doi.org/10.1016/j.jclepro.2012.05.021>

- Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). *What a waste 2.0: a global snapshot of solid waste management to 2050*. World Bank Publications.
- KCC, Khulna City Corporation, 2023. <https://khulnacity.portal.gov.bd/>. (Accessed 10 August 2023).
- Kundariya, N., Mohanty, S. S., Varjani, S., Ngo, H. H., Wong, J. W., Taherzadeh, M. J., ... & Bui, X. T. (2021). A review on integrated approaches for municipal solid waste for environmental and economical relevance: Monitoring tools, technologies, and strategic innovations. *Bioresource technology*, 342, 125982.
- Lead, C., Adedipe, N. O., Sridhar, M. K. C., & Verma, M. (2005). Waste management, processing, and detoxification. *Ecosystems and human well-being: Policy responses*, 313-334.
- Lino, F. A. M., & Ismail, K. A. R. (2012). Analysis of the potential of municipal solid waste in Brazil. *Environmental Development*, 4, 105-113.
- Matter, A., Dietschi, M., & Zurbrügg, C. (2013). Improving the informal recycling sector through segregation of waste in the household—The case of Dhaka Bangladesh. *Habitat International*, 38, 150-156.
- Modak, P.; Wilson, D.C.; Velis, C. Waste management: Global status. In *Global Waste Management Outlook*; UNEP: Athens, Greece, 2015; pp. 51–79. ISBN 9789280734799.
- Nanda, S., & Berruti, F. (2021). A technical review of bioenergy and resource recovery from municipal solid waste. *Journal of hazardous materials*, 403, 123970.
- Narayana T (2009) Municipal solid waste management in India: from waste disposal to recovery of resources? *Waste Manag* 29:1163 1166. <https://doi.org/10.1016/j.wasman.2008.06.038>
- Ogwueleka, T. C. (2013). Survey of household waste composition and quantities in Abuja, Nigeria. *Resources, Conservation and Recycling*, 77, 52-60.
- Ouda, O. K., Raza, S. A., Al-Waked, R., Al-Asad, J. F., & Nizami, A. S. (2017). Waste-to-energy potential in the Western Province of Saudi Arabia. *Journal of King Saud University-Engineering Sciences*, 29(3), 212-220.
- Roy, H., Alam, S. R., Bin-Masud, R., Prantika, T. R., Pervez, M. N., Islam, M. S., & Naddeo, V. (2022). A review on characteristics, techniques, and waste-to-energy aspects of municipal solid waste management: Bangladesh perspective. *Sustainability*, 14(16), 10265.
- Sabir Syed, 2006, Solid and Liquid Waste Management, Emirates Journal for Engineering Research, Vol: 11, No: 2, PP: 19- 36. Sifang Kong, Hui Liu, Hui Zeng, Yangsheng Liu, 2012, The Status and Progress of Resource Utilization Technology of E-Waste Pollution in China, the 7th International Conference on Waste Management and Technology, Procedia Environmental Sciences, vol: 16, PP: 515- 521.
- Samaha, B. (2013). The importance of the 3R principle of municipal solid waste management for achieving sustainable development. *Mediterranean journal of social sciences*, 4(3), 129-135.
- Shah, A. V., Singh, A., Mohanty, S. S., Srivastava, V. K., & Varjani, S. (2022). Organic solid waste: Biorefinery approach as a sustainable strategy in circular bioeconomy. *Bioresource technology*, 349, 126835.
- Shekdar, A. V. (2009). Sustainable solid waste management: An integrated approach for Asian countries. *Waste management*, 29(4), 1438-1448.
- Tonini, D., & Astrup, T. (2012). Life-cycle assessment of a waste refinery process for enzymatic treatment of municipal solid waste. *Waste Management*, 32(1), 165-176.
- Torretta, V., Ferronato, N., Katsoyiannis, I. A., Tolkou, A. K., & Airoidi, M. (2016). Novel and conventional technologies for landfill leachates treatment: A review. *Sustainability*, 9(1), 9.
- Varjani, S., Shahbeig, H., Popat, K., Patel, Z., Vyas, S., Shah, A. V., ... & Tabatabaei, M. (2022). Sustainable management of municipal solid waste through waste-to-energy technologies. *Bioresource technology*, 355, 127247.
- Velis, C. A., & Cook, E. (2021). Mismanagement of plastic waste through open burning with emphasis on the global south: a systematic review of risks to occupational and public health. *Environmental Science & Technology*, 55(11), 7186-7207.
- Wagner, T. P., & Raymond, T. (2015). Landfill mining: Case study of a successful metals recovery project. *Waste Management*, 45, 448-457.
- World Bank, 2005, Waste Management in China: Issues and Recommendations, East Asia Infrastructure Department Working Paper N: 9, PP: 7-60.