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Municipal Solid Waste to Energy Strategies in Pakistan And Its Air Pollution Impacts on The Environment, Landfill Leachates: A Review

Mohammad Siddique[1,*] Zakiyyu Muhammad Sarkinbaka[2], Aminullah Zakariyyah Abdul[3], Muhammad Asif[4], Noureddine Elboughdiri[5]

[1]Department of Chemical Engineering, Balochistan University of Information Technology, Engineering and Management Sciences, Quetta, Pakistan.
[2]Department of Chemical Engineering, Faculty of Engineering, Federal University Wukari, Taraba State, Nigeria.
[3]Department of Chemical Engineering, Faculty of Engineering, Federal University Wukari, Taraba State, Nigeria.
[4]Department of Energy and Environment Engineering, Faculty of Agriculture Engineering, Sindh Agriculture University, Tandojam, Sindh, Pakistan.
[5] Department of Chemical Engineering, College of Engineering, University of Hail, Hail, Saudi Arabia.
siddiqnasar786@gmail.com[1], zakiyyu@fuwukari.edu.ng[2], aminullahzakari234@gmail.com[3], engr.asif86@yahoo.com[4], ghilaninouri@yahoo.fr[5]

Abstract: Waste-to-energy operations are gaining importance globally because of the expanding demand for low-cost energy sources. By lowering the need for landfills and producing electricity from municipal solid waste, these methods help Pakistan to manage its solid waste. Identifying and evaluating toxicological hazards associated with the principal air pollutants emitted throughout the WtE conversion process have been the main objectives of this investigation. The different types of solid waste and emission restrictions by country and state are directly tied to the standards for air quality and the steps required to eliminate such emissions. The technical and financial viability of WtE facilities is negatively impacted by Pakistan's wet solid waste percentage, which is much greater than its dry solid waste percentage. When garbage is not properly segregated, its heating value decreases dramatically, which is bad for pollution and electricity production. The text goes into great length on these issues related to solid waste management. In this review article, WtE plants in Pakistan are contrasted with those in other countries, particularly Europe. The article has discussed ways to lessen air pollution and the harmful effects of pollutants released by WtE plants on people's health. Environmental impact assessments have also been used to analyze the benefits and drawbacks of WtE facilities about more traditional methods of managing solid waste, such as landfills, which emphasizes the significance of the ongoing study.

Keywords: Solid Waste to Energy; Air Pollution; Environment; Landfill Leachates; Municipal Solid Wastes; Toxicological Hazards; Small Biomass Generation; Anaerobic Treatments.

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1. Introduction

As the world embraces sustainable growth, the imperative to balance energy demands with environmental preservation has led to a paradigm shift from conventional to renewable resources. Nations globally are now actively assessing their waste management capabilities to harness energy from solid waste, aligning with the sustainable trend. Notably, developed countries

*Corresponding author.

like the US have pioneered waste-to-energy (WtE) initiatives, effectively addressing waste-related environmental challenges. The escalating shortage of landfill space, evident in cities like Montreal and Toronto resorting to shipping unprocessed waste to underdeveloped nations, emphasizes the urgency for alternative solutions.

To meet the general population's energy needs without negatively affecting the environment, trends in this era of sustainable growth are shifting away from conventional (non-renewable) resources and towards renewable ones. A global initiative is underway to assess each nation's capability for managing solid waste and using that knowledge in energy recovery. Developed nations like the US are aware of the possibilities for using rubbish as a source of renewable energy [1]. Developed nations are already using waste to energy (WtE) to address several waste-related environmental issues. There is already evidence of a shortage of space for disposing of municipal solid waste in many countries and towns. Cities like Montreal, Toronto, and others must ship unprocessed waste to underdeveloped countries and transfer hundreds of tonnes of trash daily from the metropolis to a remote disposal facility. More than 66% of towns in nations like China have already surpassed their dump site capacity.

Energy waste (WtE) conversion utilizing municipal solid wastes (MSW) is becoming more and more significant due to a lack of landfill space, the speed at which WtE techniques reduce waste volume, as well as the fact that it can be used to generate both electricity and heat and provide a financial incentive through the recovery of valuable components like metals, plastics, and other recyclable solid waste. Even with the best segregation methods, the segregated solid waste used as WtE feedstock still contains a considerable amount of recyclable material [2]. The most popular and oldest waste-to-energy technology is incineration, one of the various available processes. However, because of numerous local considerations like energy needs, culture, climate, economic development, etc., appropriate technologies vary from one country to the next. The type and makeup of MSW is one such crucial aspect. According to research, developing nations like India have MSW with higher moisture and organic content levels than European and North American countries, which primarily contain inorganic materials. The EU currently employs 22% renewable energy and has met its goals for reducing CO2 emissions (Table 1).

Table 1: Benefits and drawbacks of biological treatments that are aerobic and anaerobic [4]

	Aerobic	Anaerobic
Advantages	Low HRT	Needs low energy
	High SRT	It can create biogas with a high CH4 content and act as a net energy producer.
	A tiny amount of sludge production	Small biomass generation
	Internal to the system is biological active mass.	Less P is needed as an inducer for the growth of anaerobic bacteria.
	Efficient in breaking down organic matter.	Lower energy consumption.
	Reduced odors due to aerobic conditions.	Methane production can be harnessed for energy.
	Well-suited for treating municipal wastewater.	Effective in treating high-strength industrial wastewater.
	Nutrient removal	High BOD and COD are required.
Disadvantages	Significant levels of dissolved oxygen are necessary for N_2-fixation in biofilm reactors.	Longer start-up time.
	Challenges with fixed bed setups due to overcrowding.	Sensitive to various hazardous chemicals, including HMs and NH_3, as well as variations in temperature and pH.
	Energy-intensive process.	Slower treatment compared to aerobic processes.
	Higher operational costs.	Odor issues in some cases.
	Produces excess sludge.	Sensitivity to pH and temperature fluctuations.

The EU aims to use 32% or more renewable energy by 2030 and cut greenhouse gas emissions by 55%. The EU could adhere to a prioritized waste treatment or management program and still meet its 2020 pre-established targets. From highest to lowest priority, the following are listed: (a) avoidance, (b) reusing, (c) recycling, (d) recovery, and (e) garbage dump. This study's objective is to address a few unsolved issues that may aid Pakistan in developing appropriate WtE technologies in the future in light of the preceding. The goals of this paper are (a) a quantitative review of Pakistan's potential and installed capacity for WtE in various states and comparison with the WtE sector in Europe and other developed nations, (b) an identification of major emissions and air pollutants from WtE facilities, (c) a qualitative review of the health risks for those who live nearby such facilities, and (d) an identification of factors that significantly impede the development of the Pakistan Pact [3] (Table 2).

Table 2: Efficiency, Cost-effectiveness, and Environmental Impact of aerobic and anaerobic Treatment

	Efficiency	Cost-effectiveness	Environmental Impact
Aerobic Treatment	Aerobic treatments excel in breaking down organic matter efficiently. Oxygen allows for the complete oxidation of organic compounds, yielding high treatment efficacy.	While initial setup costs can be higher due to the need for aeration systems, aerobic processes often result in lower operational costs in the long run. Maintenance and energy consumption can be offset by enhanced treatment efficiency.	Aerobic treatments generally have a lower environmental impact compared to anaerobic methods. The end products are often less harmful, and the process promotes the growth of aerobic microorganisms that contribute to overall ecosystem health.
Anaerobic Treatment	Anaerobic treatments effectively break down organic matter but may be slower than aerobic processes. The absence of oxygen limits the complete oxidation of organics, leading to the production of byproducts like methane.	Anaerobic treatments can be cost-effective regarding operational costs, as they often require less energy. However, initial setup costs may be lower due to the simplicity of anaerobic systems.	The environmental impact of anaerobic treatments is a bit more complex. While they produce methane, a potent greenhouse gas, the overall impact can be mitigated through proper gas management and utilization.

Choosing between aerobic and anaerobic biological treatments depends on specific wastewater characteristics, treatment goals, and environmental considerations. Aerobic processes offer high efficiency with manageable operational costs, while anaerobic processes can be cost-effective but require attention from product management.

2. MSW Characteristics

The crucial factors for effective management, treatment, and disposal of Municipal Solid Waste (MSW) are its sources and the physical and chemical components. MSW originates from three main categories: urban, industrial, and rural. Within the urban division are residential and non-residential wastes, such as commercial, institutional/service, construction, and special types of waste, including those from scientific experiments, medical facilities, manufacturing, automobile maintenance shops, pharmacies, and airports. Industrial waste is produced in industrial sites during processes like extraction, utilization, modification, and production of goods and services, along with the delivery of goods. The rural division encompasses agricultural items like fertilizers, animal byproducts, and animal husbandry waste. This hierarchy is illustrated in Figure 1.

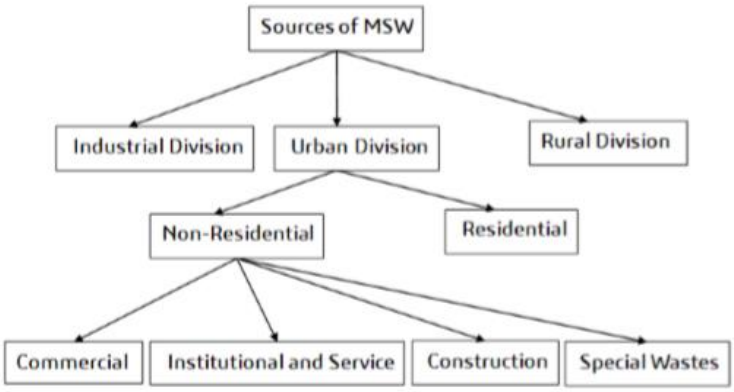

Figure 1: Differentiated Origins of Municipal Solid Waste [5]

The municipal solid waste (MSW) components contribute to its corrosive, ignitable, reactive, toxic, infectious, and occasionally radioactive nature (refer to Fig 2). For instance, strong alkaline or acidic waste falls under the corrosive category, posing a threat to the environment, soil, and landfill cells upon disposal. Ignitable waste, characterized by its propensity to burn at lower temperatures, poses an immediate risk of fire and explosion. Chemically unstable and reactive wastes exhibit aggressive reactions with air or water. Toxic waste, even in trace amounts, can have severe health implications, potentially leading to death or catastrophic diseases.

In infectious waste, items like hospital bandages and medical hypodermic needles contribute to this category, necessitating careful disposal. Radioactive waste, emitting hazardous radioactive energy, poses some long-term threats as certain elements may remain active for thousands of years, potentially causing harm to humans, animals, and plants in their vicinity. It is imperative to address these diverse characteristics of MSW for effective waste management and environmental protection.

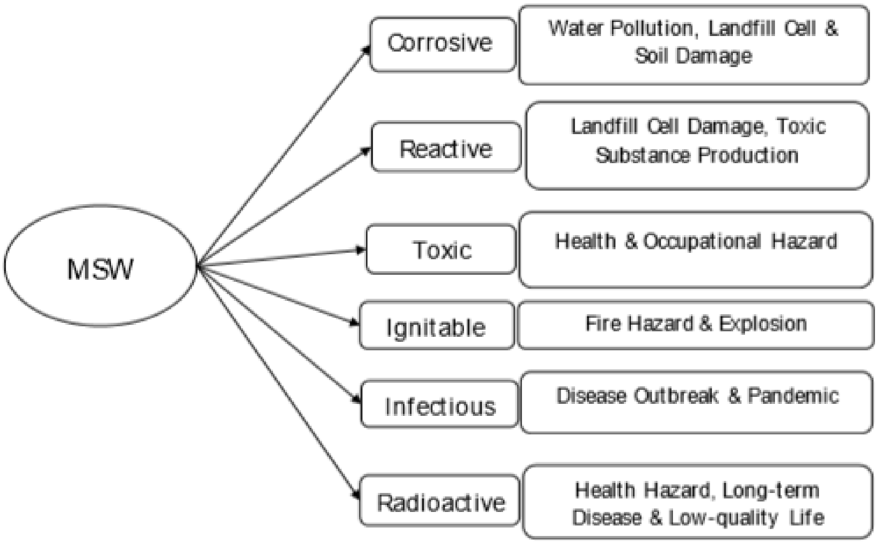

Figure 2: Properties of MSW [5]

3. Waste generation, characteristics and composition

Before choosing and applying Waste-to-Energy (WTE) technologies, it's crucial to understand the quantity, characteristics, and composition of generated waste. According to the 2012 World Bank report, the global Municipal Solid Waste (MSW) generation rate was 1.3 billion tonnes annually, averaging 1.2 kg/c/d. Projections indicate an expected increase to 2.2 billion tonnes by 2025 and a staggering 4.2 billion by 2050. The MSW generation rate aligns with the Gross Domestic Product (GDP) of developing countries, as illustrated in Fig 3, categorizing nations into developed and developing based on GDP per capita. Countries with GDP per capita exceeding US$ 10,000 were labeled as developed. Notably, some developed nations like Iceland, Japan, Singapore, Sweden, Australia, and Norway displayed lower MSW generation rates, possibly due to diverse MSW definitions and waste reduction policies, as seen in Japan. Developed countries typically range from 1.00 to 2.50 kg/c/d, while developing countries range from 0.50 to 1.00 kg/c/d.

Understanding municipal solid waste (MSW) characteristics and composition is crucial before selecting and implementing Waste-to-Energy (WTE) facilities for effective city management. Key factors like particle size, moisture content, calorific value, and density are pivotal in energy production. These attributes vary not only between developed and developing countries but also among cities within the same nation due to the heterogeneous nature of MSW. Analyzing waste characteristics involves considering socioeconomic profiles, climatic conditions, recycling practices, collection frequency, and demography.

A classification based on previous studies identifies six components in the waste stream: kitchen/yard waste, paper/cardboard, plastic, metals and glass, inert, and miscellaneous. Notably, MSW in developed countries tends to have lower moisture content (20-30%, e.g., USA, European countries) than in developing nations (50-70%, e.g., China, India). Additionally, the calorific values in developed countries are higher (2000–4000 kcal/kg) due to a significant presence of paper and dry organic wastes, while developing countries exhibit lower values (700–1600 kcal/kg). High-income countries show a lower decomposable organic fraction (below 30%) and a higher fraction of plastics, paper, textiles, and recyclable wastes, whereas developing countries have an organic content exceeding 50%.

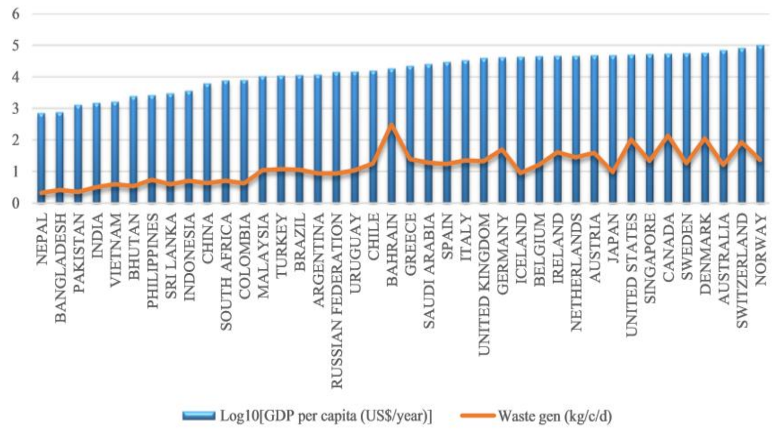

Figure 3: Distribution of Waste generation rate and GDP of the different countries [6]

4. Landfill Leachate

Landfill leachate, originating from waste treatment plants, landfills, and more, raises environmental concerns due to its high concentrations of organic matter, toxic chemicals, heavy metals, and more. The refractory compounds, like humic acids, dominate the organic fraction. This leachate exhibits acute and chronic toxicity, is classified as hazardous, and poses groundwater contamination risks, especially in low-lying areas and during extreme weather events. In developing countries with inadequate landfill infrastructure, leachate percolation into groundwater is a significant issue. Prevention involves proper leachate collection systems. Treatment methods, including anaerobic and aerobic biological processes, physicochemical treatments, coagulation, and adsorption, are crucial for making leachate safe for disposal. The choice of treatment depends on factors like chemical oxygen demand and biological oxygen demand.

In Pakistan, an in-depth study delved into groundwater contamination near landfill sites, drawing parallels with findings in China. Factors such as landfill age, waste composition, and seasonal variations were identified as crucial influencers on the contamination landscape. Heavy metals, xenobiotics, and pathogens emerged as significant contaminants, directly threatening groundwater quality. Notably, unregulated landfills were pinpointed as major contributors, rendering shallow groundwater in certain areas unsuitable for consumption due to elevated concentrations of pollutants. The pollutants in landfill leachate pose health risks to humans terrestrial, and aquatic animals. Diseases like Minamata, arsenicosis, and cancer can result from exposure to toxic elements beyond permissible limits. Despite these threats, quantifying direct health hazards remains challenging due to a lack of comprehensive exposure studies. Planning is essential when creating landfills. The right monitoring, risk assessment, and leachate treatment employing cutting-edge technologies are required to prevent leachate toxins from entering the soil and groundwater. Certain waste materials must always be disposed of in Fig. 4 unless considerable concentrations of waste avoidance, reuse, biodegradable, safe items, and recycling are attained. Therefore, this problem needs to be addressed via sustainable landfills. A landfill is considered fully sustainable when waste is safely incorporated into the ecosystem. The framework of this study, which was created following an extensive review of the literature, may be used by all parties involved in the landfill sector to analyze the environmental effects of landfills [7].

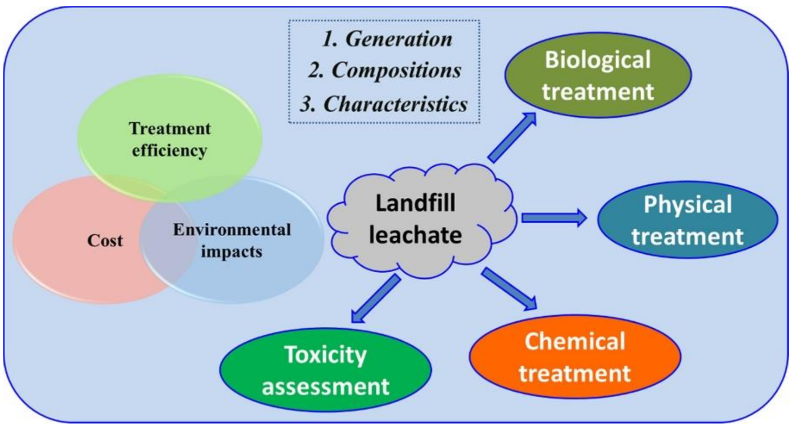

Figure 4: Municipal landfill leachate [8]

5. Landfill Gases

Landfills generate gases through various thermal, chemical, and biological reactions. In Pakistan, municipal solid waste contributes to these gases, containing compounds like alcohol and naphthalene. Fig. 5 illustrates that landfill gas formation involves complex mechanisms, including hydrolysis, fermentation, anaerobic oxidation, acidogenesis, acetogenesis, and methanogenesis. Methanogenic bacteria play a crucial role in anaerobic decomposition, producing methane (CH4) and carbon dioxide (CO2). Landfill gas, with its major components CH4 and CO2, is a significant contributor to global warming, with CH4 having a higher impact. In the USA, landfills rank third in CH4 emissions. Landfill gas composition varies based on waste properties, decomposition phase, oxygen availability, moisture, pH, and microbial population. Besides environmental concerns, the high CH4 concentration poses risks of fires and explosions. Landfill gases also contain non-methane organic compounds, including hazardous air pollutants, volatile organic carbons, and odorous compounds. Flaring landfill gases can emit harmful substances like dioxins and furans, with potential carcinogenic effects upon regular exposure.

Landfill gases, generated within 0.5–3 years of waste disposal, diminish as the landfill matures. Timely recovery within three years is crucial. Extracted crude landfill gas is water-contaminated with chlorinated hydrocarbons. After separation, the water is mixed with leachate. Besides causing unpleasant odors, gas emissions from landfills pose health risks to nearby residents and operators. Long-term exposure may result in various health issues, from emotional stress to respiratory problems. While concerns exist, epidemiological evidence on health implications and mortality from landfill gases is limited and inconsistent. In the context of Pakistan's municipal solid waste-to-energy strategies, managing landfill gases is pivotal for mitigating air pollution and safeguarding public health.

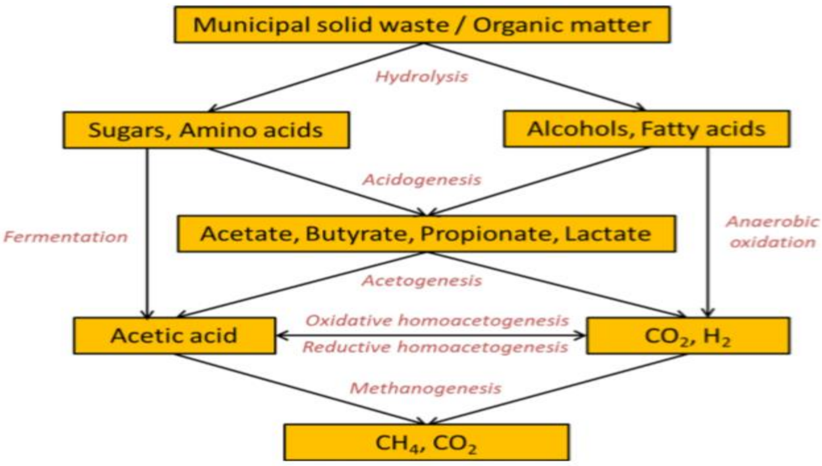

Figure 5: Mechanism of landfill gas formation in sanitary landfills. Landfill gas formation includes diverse chemical processes like hydrolysis, fermentation, anaerobic oxidation, acidogenesis, acetogenesis, and methanogenesis [9]

6. Limitations and significant national issues include financial scarcities and policy inconsistencies

In the context of Pakistan's municipal solid waste-to-energy strategies, it's vital to note that similar challenges exist, such as financial scarcity and policy inconsistencies. The limitations faced by Pakistan parallel those encountered by Vietnam, with both nations grappling with a lack of resources and policy compatibility issues. The dense population, low per capita income, and substantial garbage volume in Pakistan contribute to labor-intensive and financially burdensome waste collection and treatment systems. The government, facing challenges in covering these expenses, encounters hindrances akin to those in Vietnam. Moreover, investment calls in Pakistan may be limited, mirroring the situation in Vietnam [10]. Like their Vietnamese counterparts, local governments in Pakistan may perceive national waste management policies as unsuitable for their unique circumstances. Pakistan's diverse human, natural, social, and environmental variables and distinct developmental scenarios necessitate a nuanced approach to policy implementation. The nation's administrative structure, comprising provinces with varying sizes, populations, and management methods, further complicates the uniform application of national policies. Recognizing the need for tailored programs based on each community's circumstances becomes crucial.

Citing these challenges, it becomes evident that applying a one-size-fits-all policy across diverse regions, be it in Vietnam or Pakistan, presents practical difficulties. Vietnam's experience highlights the importance of understanding the specificities of each locality for effective waste management programs. These constraints and challenges impede the economic progress of both nations. While drawing parallels between Pakistan and Vietnam's waste management challenges, it's imperative to consider the unique aspects of each country's situation. Adapting policies to local circumstances becomes paramount for successful implementation. The economic impact of these limitations underscores the urgency of addressing these issues in both nations [11].

7. Major national difficulties include financial constraints and inconsistencies in policy

One of the major national difficulties that loom over Pakistan's waste-to-energy initiatives is the persistent issue of financial constraints. Insufficient funds earmarked for waste management projects have hindered the country's ability to make significant strides in this arena. These financial limitations have repercussions at multiple levels, affecting the capacity to invest in advanced waste-to-energy technologies and the feasibility of operating and maintaining such systems effectively. This financial problem can be expressed mathematically as follows:

$$\text{Funds}_{\text{WtE}} < \text{Funds}_{\text{required}} \quad (1)$$

$\text{Funds}_{\text{WtE}}$ Represents the available funds for waste-to-energy projects.

$\text{Funds}_{\text{required}}$ Indicates the financial resources necessary for the successful implementation and sustained operation of waste-to-energy infrastructure.

Inconsistencies in policy further compound the challenges. While national policies are intended to provide a framework for waste management practices, there is often a contradiction between these policies and the ground realities local communities face. The lack of alignment between national policies and local needs creates a policy-implementation gap that hinders progress. This discord can be depicted through the equation:

$$\text{Policy}_{\text{incompatibility}} = \sum_{i=1}^{n}(\text{Policy}_i - \text{Local}_i) \quad (2)$$

$\text{Policy}_{\text{incompatibility}}$ Measures the extent of policy incompatibility across multiple domains (i) between national policies (Policy_i) and local requirements (Local_i).

In the specific case of Pakistan, the challenges are exacerbated by its dense population, low per capita income, and the sheer volume of garbage generated daily. This trio of factors translates into a dire need for extensive labor and operational expenses to manage and process waste effectively. This financial burden on the government can be expressed as:

$$\text{Expense}_{\text{gonernment}} = \text{Labor}_{\text{cost}} + \text{Operational}_{\text{cost}} \quad (3)$$

$\text{Expense}_{\text{gonernment}}$ Represents the total expense incurred by the government for waste management.

$\text{Labor}_{\text{cost}}$ Accounts for the costs associated with labor employment in waste collection and processing.

$\text{Operational}_{\text{cost}}$ Denotes the expenses related to the operational aspects of waste management facilities.

In addition, Pakistan's waste management challenges are not uniform across the country. Each province boasts a unique territory, population, and governmental setup. The 'one-size-fits-all' approach embodied in national policies often clashes with the diverse local contexts. Mathematically, this can be illustrated as:

$$\text{Policy}_{\text{uniformity}} \neq \forall \text{ Provinces} \quad (4)$$

$\text{Policy}_{\text{uniformity}}$ Represents the attempt to apply the same policy consistently across all provinces.

Understanding these intricate challenges in terms of financial constraints and policy discrepancies is crucial for devising effective strategies for municipal solid waste to energy in Pakistan. These equations provide a quantitative lens through which we can assess and address these challenges, ultimately steering the nation toward sustainable waste management practices [12].

8. Policy implementation in some nations

To elaborate on the municipal solid waste-to-energy strategies in Pakistan and its air pollution impacts on the environment and landfill leachates, it is crucial to investigate the specific methodologies employed in waste-to-energy conversion. Pakistan's approach may include incineration, anaerobic digestion, or gasification, each with environmental implications. For instance, incineration raises concerns about air quality due to emissions, while anaerobic digestion might mitigate these issues but poses challenges regarding infrastructure and technology adoption. In examining policy implementation in different nations, it's noteworthy to highlight how Indonesia and Brazil have tackled waste management challenges. Indonesia's success could be attributed to robust collaboration among stakeholders, including municipal administration, corporate entities, NGOs, and educational institutions. This multi-faceted involvement ensures a more comprehensive and effective implementation of solid waste management policies. On the contrary, Brazil faces obstacles such as funding shortages, limited technology, and community involvement issues [13]. Tightening policy execution, allocating sufficient resources, and emphasizing environmental managers' capacity are recommended solutions for Brazil.

Furthermore, drawing parallels with Japan and Taiwan can provide insights into overcoming challenges associated with waste management legislation. These nations may offer examples of effective monitoring and enforcement mechanisms, shedding light on how such strategies can be applied in the Pakistani context. Addressing weak administration, lack of stakeholder commitment, and social components is crucial for the success of Pakistan's solid waste management strategy. To meet the word count requirement, it's beneficial to expand on the specific technologies used in waste-to-energy processes, their environmental impacts, and the potential challenges and solutions in implementing these strategies [14]. This can provide a more comprehensive analysis of Pakistan's waste management scenario and its lessons from other nations.

9. Solid Waste LFL Applications

Solid waste from various sources presents challenges and opportunities for creating value-added products. Municipal food waste, in particular, holds immense potential for conversion into valuable resources. Despite the potential, effective conversion methods are currently lacking, primarily due to the diverse nature of the waste stream, leading to technological limitations. Future researchers should explore innovative strategies to address the challenges posed by waste heterogeneity. However, costly, energy-intensive, integrated pyrolysis machines offer an environmentally friendly solution for breaking down municipal solid waste [15]. However, biomass furnaces face difficulties when dealing with agricultural solid waste containing high ash content, as seen in soy straw. A potential solution lies in co-firing biomass with lower ash content, mitigating operational challenges. The processing of lignocellulose, an agricultural solid waste, holds promise for producing various chemical and biological substances with applications in textile, material, biomedical, and pharmaceutical industries. However, this approach raises concerns about excessive energy and water use, chemical exposure, and challenges related to the collection, transport, and disposal of lignocellulosic waste, necessitating further investigation.

Another sustainable waste management avenue involves recovering rare, valuable metals from industrial waste. This approach addresses resource constraints and requires careful consideration to minimize secondary contamination during the precious metal recovery process. Waste generated by paper mills offers opportunities for producing technically advanced products, including biocomposites, cellulose nanocrystals, bioplastics, and carbon fibers. Implementing suitable and eco-friendly methods for biomaterial production can lead to multifunctional bio-based products with applications across conventional, high-performance, and intelligent sectors [16]. Future applications of municipal solid waste will likely require the development of integrated solar heating systems to overcome technological constraints and enhance overall value.

Moreover, to prevent resource waste, exploring new chemicals and technologies for agricultural solid waste value addition is crucial [17]. In industrial solid waste, Fig. 6 illustrates existing value-added technologies, emphasizing the need for further exploration into the use of bacterial cultures and tighter parameter monitoring to optimize the processes. The mission for sustainable waste management and value creation from solid waste streams demands interdisciplinary research, innovative technologies, and a holistic approach to address environmental, economic, and social challenges.

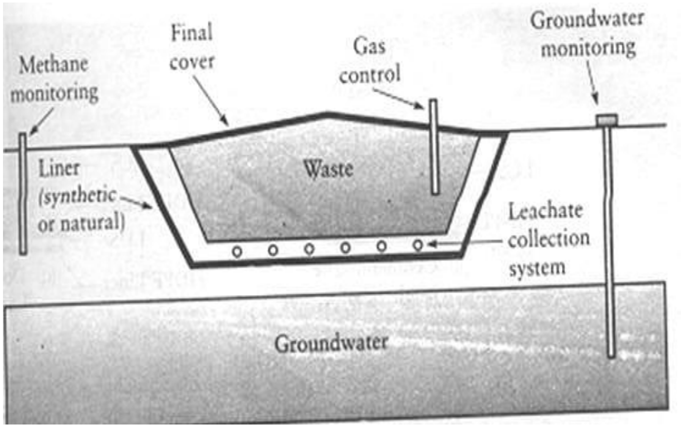

Figure 6: Methods of Solid Waste Disposal and Management [18]

10. Treatment for LFL in the future

Cities worldwide produce 2.01 billion metric tonnes of MSW annually, and due to urbanization, rapid population expansion, and economic development, that amount is anticipated to increase to 3.40 billion tonnes by 2050. For national and local authorities in many cities throughout emerging and industrialized countries, the solid waste problem is of paramount concern. Landfills are frequently used for solid waste disposal, particularly in poorer nations, where they are more affordable to set up and maintain than other methods. Examining potentially harmful substances, including polymers, halogenated chemicals, and toxic HMs, is also critical.

Figure 7: Potential impact of landfills on the environment [20]

In addition to their benefits for the environment and the economy, microorganism-based solutions offer a desirable alternative to remove and detoxify leachate. There are several benefits to researching how microorganisms efficiently remediate leachate, but there is still much to learn. New microorganisms that effectively remediate leachate could be adapted using contemporary techniques (such as metagenomics). Leachates from older landfills have been successfully biologically remedied in the past. Leachates from former landfill sites can be treated more effectively using biological, physical, and chemical methods [19]. Pollutants close to landfills can be naturally removed through phytoremediation in addition to aerated lagoons. Reuse and recycling must be carefully examined to decrease the amount of solid and hazardous waste in the contemporary environment, as presented in Fig. 7.

11. Conclusion

In Pakistan, waste-to-energy conversion still represents a sizable untapped energy potential. A developing nation like Pakistan has a high requirement for energy, making affordable and sustainable energy crucial. The Pakistani government's many initiatives have increased our waste energy potential (biomass, MSW). The capacity for biomass energy generation has increased significantly in the last ten years (10 GW), but the potential for MSW-based energy has not yet been fully realized. It must be emphasized that less than 5% of the potential electricity production from MSW is being used in Pakistan. This assessment aimed to discuss the benefits and drawbacks of the technology used in the Pakistani WtE sectors. The paper provides information on Pakistan's full energy potential and the installed capacity for WtE electricity generation in different Pakistani areas. The research emphasizes the disparities between the global and Pakistani WtE situations. This report spends a lot of time analyzing air pollution risks associated with WtE facilities and offering mitigation solutions. A discussion of the environmental impact studies of WtE technologies is also included in the paper. This paper reviews the major elements that must be considered when designing or building a WtE plant, and it suggests the optimal plant solutions based on cost-effectiveness and environmental friendliness in various scenarios. Several difficulties and obstacles have been put up that limit the successful execution of several Pakistani waste-to-energy projects. A policy framework efficiently supports garbage recycling. For efficient policy implementation on the ground, participation of governmental, non-governmental, and educational parties is actively encouraged.

Despite the substantial progress in increasing biomass energy generation in Pakistan, the underutilization of municipal solid waste (MSW) for energy production remains a significant challenge. The environmental impact studies presented in this assessment underscore the need for a comprehensive approach to address air pollution risks associated with waste-to-energy facilities. While the government's initiatives have boosted awareness and laid the foundation for sustainable practices, the paper suggests a more focused strategy to unlock the full potential of MSW-based energy. Bridging the gap between the global and Pakistani waste-to-energy situations requires targeted investments, technology upgrades, and collaborative efforts from stakeholders. As the nation grapples with obstacles hindering the successful execution of waste-to-energy projects, a renewed emphasis on policy frameworks supporting garbage recycling and responsible waste management is crucial. In conclusion, optimizing MSW-based energy production in Pakistan demands technological advancements and a synchronized effort from governmental, non-governmental, and educational entities for effective policy implementation on the ground.

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