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A Comprehensive Review of Engineering Strategies for Environmental Sustainability in Sustainable Waste Management

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ABSTRACT: Waste management and environmental sustainability are intricately linked aspects crucial for maintaining ecological balance and human well-being. This study synthesizes research findings and scholarly insights to underscore the significance of effective waste management practices in achieving environmental sustainability goals. It examines waste treatment approaches, including recycling, waste-to-energy systems, and waste reduction strategies, highlighting their role in mitigating environmental impact. Additionally, the study explores the environmental consequences of inadequate waste management, emphasizing the urgent need for holistic solutions to address water, soil, and air pollution. Engineering solutions for sustainable waste management, such as the 3R principle (Reduce, Reuse, Recycle), thermal treatment methods, and landfill management, are discussed as essential components of a comprehensive strategy. By integrating these approaches, policymakers, industries, and communities can minimize waste generation, conserve resources, and safeguard the environment for current and future generations. Challenges like regulatory barriers, lack of awareness, and inadequate infrastructure pose obstacles to sustainable waste management practices. Thus, a collaborative effort involving governments, businesses, and civil society is crucial to implementing effective waste management policies and initiatives. Through concerted action, we can transition to a circular economy model that promotes resource efficiency, environmental protection, and human well-being on a global scale.

KEYWORDS: Circular Economy, Environmental Sustainability, Engineering Approaches, Sustainable Waste Management, Waste Reduction Strategies.

INTRODUCTION

Effective waste management is imperative for sustaining environmental health and public well-being, particularly in regions experiencing rapid urban growth. Each type of waste—solid, liquid, and gaseous—presents unique challenges that require specialized management strategies. Urban centers, in particular, struggle with the substantial amounts of waste generated on a daily basis. In Kabul, Afghanistan, the deficiencies in waste management infrastructure have led to critical environmental and public health crises (Moghadam et al., 2015). The reliance on traditional landfill methods is increasingly inadequate in addressing the burgeoning waste volumes, underscoring the urgent need for adopting more sophisticated and sustainable waste management approaches. These advanced practices are vital to mitigating the negative impacts of waste on the environment and public health (Williams, P. T. (2013).

Urban waste, including Municipal Solid Waste (MSW), Commercial and Industrial (C&I) waste, and Construction and Demolition waste (C&D), is estimated to total 7 to 10 billion tons annually (United Nations Environment Program (UNEP) report, 2015). Moreover, the construction industry accounts for 35% of global waste, making it the main source of solid waste (Jyoti Prakash, 2023). The impact of waste from tourism companies is also significant, with the industry generating 35 million tons of solid waste annually worldwide.(Banar, and Özkan, 2007).

In the domain of municipal solid waste (MSW), plastic content varies from 7% to 12%, displaying little correlation with income levels. 'Dry recyclable' materials range from 12% in high-income to 6% in low-income countries. Household Hazardous Waste (HHW) makes up less than 1% of MSW. Incinerators contribute to air pollution, and inadequate solid waste management practices, influenced by urbanization and financial constraints, pose environmental and health hazards, particularly affecting marginalized communities (Choudhari et al., 2019; Abubakar et al., 2022). A significant amount of household waste, ranging from 20% to 80%, is frequently improperly disposed of in open spaces, water bodies, drains, or subjected to burning or burial. This widespread practice results in unsanitary environments that contribute to health hazards (Istrate et al., 2020; United Nations Environment Program (UNEP) report, 2015).

Recycling and waste-to-energy (WTE) technologies have emerged as highly effective strategies for mitigating the environmental footprint of waste. Recycling plays a critical role in conserving natural resources and significantly cutting down the energy consumption and greenhouse gas emissions associated with the production of new goods (Hopewell et al., 2009). On the other hand, WTE technologies, such as incineration and anaerobic digestion, offer a dual benefit by converting waste materials into usable energy forms, thereby reducing the volume of waste destined for landfills and contributing to the generation of renewable energy (Pires et al., 2011).

Adopting the 3R approach—Reduce, Reuse, Recycle—has gained significant support as a means to minimize waste production and enhance resource efficiency (Ghisellini et al., 2016). This strategy emphasizes reducing waste generation at the source, reusing products to extend their lifecycle, and recycling materials to reintegrate them into the production cycle, thus promoting a circular economy. Implementing effective waste segregation practices and ensuring proper disposal methods are also vital elements of comprehensive sustainable waste management strategies (Singh et al., 2014). By adhering to these principles, communities can significantly reduce their environmental footprint, conserve resources, and create a more sustainable and efficient waste management system.

Beyond technological solutions, effective waste management systems depend significantly on well-designed policy frameworks and proactive community engagement. Government policies that champion sustainable waste management practices, combined with increased public awareness and active involvement, can markedly improve the efficiency and effectiveness of these systems (Yukalang et al., 2017). Engaging local communities in waste management initiatives not only enhances compliance but also fosters a sense of responsibility and ownership among residents. This engagement is essential as it promotes better waste segregation, reduces littering, and encourages more sustainable behaviors. Furthermore, educational programs and public awareness campaigns play a crucial role in reinforcing the significance of proper waste management. By making waste management a collective effort, these initiatives ensure that the entire community benefits from a cleaner and more sustainable environment (Wilson, Velis, & Cheeseman, 2006).

In countries like Afghanistan, which face resource limitations, the main causes of food loss and waste are financial, managerial, and technical obstacles in harvesting, storage, and cooling facilities (UNAMA report, 2024; UNEP in Afghanistan, 2009). Meanwhile, in Kabul city, the management of solid waste presents a significant challenge, with a daily output of 3,050 tonnes in 2018 for a population of 5 million (Khoshbeen & Logan, 2019). Recent data from Kabul highlights alarming statistics: the city produces roughly 1,500 tons of solid waste daily, of which only 20% is managed effectively. The rest is either openly burned, leading to air pollution, or disposed of in unofficial landfills, causing soil and groundwater contamination. The absence of waste segregation exacerbates the inefficient use of recyclable materials. Furthermore, localized studies, such as waste generation in Bagh-e-Babur at 23,586 kg per year, shed light on specific aspects of the broader waste management issue (Mukhtar et al., 2016).

In 2018, Kabul's solid waste production reached an astounding 3,050 tonnes per day, with projections anticipating a rise to 3,300 tonnes daily by 2025. Analysis of waste composition highlights a significant organic component of about 70%, emphasizing the urgent need for targeted interventions. Specific areas, like Bagh-e-Babur, contribute notably to yearly waste volumes, illustrating the diverse challenges in waste management faced by the city. Immediate action is crucial to implement comprehensive and sustainable waste management strategies tailored to Kabul's unique situation, integrating advanced engineering practices and technologies for environmental sustainability and public health (Mukhtar, 2016). Additionally, studies suggest that a gradual 25% reduction in waste by 2023 could decrease the overall system cost to 1505.9 million AFS per year from an estimated 2210 million AFS per year. Projections indicate a further increase in waste generation to 3,300 tonnes per day by 2025, with a per capita daily generation rising to 0.6 kg, up from 2,563 tonnes per day and 0.5 kg/day in 2020 (Shafy & Mansour, 2018).

Sustainable waste management is widely acknowledged as crucial for addressing global environmental challenges and promoting long-term well-being (Abila & Kantola, 2013). However, effective waste management begins with segregating solid waste at its source and treating different waste components differently, thereby minimizing residual waste destined for landfills. Although there is a growing understanding of solid waste management principles and increased public discourse on the topic, city officials are still in the early stages of prioritizing the collection of segregated waste and its subsequent transportation, treatment/processing, recycling, and safe disposal (Kirillova et al., 2018).

Effectively managing waste presents a major challenge in achieving global sustainable development. Various methods are available for waste disposal or treatment, including landfilling, incineration, reduction, composting, and recycling. However, landfilling remains the most commonly used method in low-income and middle-income countries due to its affordability (Yang et al., 2016). The effectiveness of landfilling depends on technical, economic, and legal frameworks, which are often inadequate in many countries. Sustainable landfilling aims to reduce environmental parameters such as methane and leachate to acceptable risk levels (inert waste) to prevent harm to humans and the environment (Osazee, 2021). Therefore, ensuring effective landfill management is crucial in preventing scavengers from accessing toxic waste sites. Additionally, the informal sector should adopt affordable emerging technologies to reduce health risks during waste recycling. For example, using saltwater flotation can separate plastics containing toxic Brominated Flame Retardants (BFRs) (Khoshsepehr et al., 2023). Furthermore, thermal treatment methods can reduce the volume of solid waste entering landfills by up to 80–90% and the mass by 65–75% (Rahman and Alam, 2020).

Researchers globally have proposed various waste management solutions, with thermal treatments like incineration, pyrolysis, and gasification being prominent. These methods effectively reduce waste volume while generating energy (Henry et al., 2005). Moreover, utilizing heat for waste treatment enables energy recovery applicable to heating or electricity generation (Rahman and Alam, 2020). Proper waste disposal plays a crucial role in maintaining environmental sustainability, with emphasis on recycling specific wastes further contributing to this goal. However, given Afghanistan's unique challenges, waste-to-energy technologies emerge as the most suitable solution. These technologies convert waste into electricity or heat, addressing waste management and providing a sustainable energy source, particularly beneficial for Afghanistan's development and environmental needs (Henry et al., 2005).

In summary, escalating waste generation, compounded by inadequate management, poses significant environmental and health risks globally. Thermal treatment, recycling, landfill, disposal, and waste-to-energy technologies emerge as vital strategies to address these challenges, particularly crucial for countries like Afghanistan facing unique waste management issues.

2. WASTES

Waste is defined as materials or objects that are discarded, disposed of, or designated for disposal (UNEP/GRID-Arendal, 2011). It is also described as "unwanted or undesirable products of life" (Gemmell et al., 1984). Additionally, waste refers to materials or objects that are thrown away, disposed of, or intended for disposal (UNEP/GRID-Arendal, 2011). According to various anthropologists and social scientists, waste serves as a reflection of humanity (Pongrácz et al., 2002). In simpler terms, waste refers to any material item that is no longer useful, or not required due to various reasons. It can be defined as anything that remains at the end of a process without utility or functionality for a user (Joshua Reno, 2015). However, waste is also a valuable secondary carbon resource. In the linear economy, it is mainly landfilled or incinerated. These disposal methods not only contribute to various climate, environmental, and societal issues but also result in a loss of carbon resources (Lee et al., 2020).

Solid waste includes garbage or discarded materials and objects resulting from industrial, commercial, mining, agricultural, and general day-to-day activities (Muhammad et al., 2023). Most human activities generate waste (Brunner and Rechberger, 2014). Despite this, waste production has long been a major concern, dating back to prehistoric times (Chandler et al., 1997). In recent times, the rate and quantity of waste generation have been increasing, leading to a greater variety of waste types (Vergara and Tchobanoglous, 2012). Unlike the prehistoric era where waste was simply seen as a nuisance requiring disposal, today's understanding of waste includes recognizing its impact on the environment and society.

3. TYPES AND CLASSIFICATION OF WASTES

3.1 Types of Waste

Waste is typically classified into three main types based on its nature: solids, liquids, and gases (Ali & Zhang, China, 2023).

3.1.1 Solid Waste

Solid wastes are produced throughout the processes of acquiring raw materials, manufacturing, and consuming products. However, these wastes are unwanted substances discarded by human society. They encompass urban, industrial, agricultural, biomedical, and radioactive wastes (Anurag Tiwari, 2013). Solid wastes are non-soluble materials or the solid portion of rejected materials from sectors like plastics, glass products, food waste, paper, wood, metals, mining residue, and more. Many solid wastes are non-recyclable and degrade slowly over time (Abinet Addis Mihiretie, 2020).

3.1.2 Liquid Waste

Liquid wastes are the result of washing, flushing, or manufacturing processes in industries. They encompass urban wastewater, sewage, effluents from industries and landfill sites, agricultural runoff, and leaching of agricultural chemicals, among others. Liquid wastes are typically transported using containers or pipes. Discharging excessive sewage into a river or water body can disrupt the delicate ecosystem, leading to the death of aquatic species such as fish (Yadav et al., 2020).

3.1.3 Gaseous Waste

Gaseous wastes are released in the form of gases from sources like automobiles, and factories, or the burning of fossil fuels such as petroleum. These gases mix with the atmosphere and can lead to events like smog and acid rain. Gaseous waste encompasses gases produced by various human activities, including those from manufacturing industries and chemical factories (Yadav et al., 2020). The gases, including methane (CH_4), carbon dioxide (CO_2), and chlorofluorocarbons (CFCs), contribute to environmental problems like pollution and climate change (Pardo et al., 2014).

3.2 Classification of Wastes

Wastes can be categorized mainly into two classes based on their source of generation and type of materials. Classification based on Source, and classification based on Type.

3.2.1 Classification Based on Sources

a) Domestic waste: Household waste is generated at the household level or from dwellings, apartments, and residential buildings. It includes leftover food, contaminated wastewater from detergent use, household garbage, ashes, furniture materials, clothes, plastics, and other materials. Domestic waste is produced through individual activities and, like other living organisms, humans release waste substances into the environment, contributing to the natural cycle. This waste can be classified into two forms: solid and liquid (Oyewo et al., 2018; Pushpakalambiga & Jasmine, 2021).

b) **Agricultural waste:** Agricultural wastes stem from agricultural areas and associated processes, comprising organic waste from plants and animals, spoiled food grains, livestock breeding byproducts, crop residue post-harvest, and contaminated water from chemical fertilizer and pesticide use, among other agricultural remains (Oyewo et al., 2018). However, these wastes can serve various beneficial purposes, such as being used as feedstock for energy production, chemical recovery, or adsorption of chemicals or dyes (Zhang et al., 2014; Pushpakalambiga & Jasmine, 2021).

c) **Industrial waste**: Industrial wastes originate from manufacturing and processing industries such as chemical plants, cement factories, power plants, textile industries, food processing industries, and petroleum industries. The growing demand due to population growth has led to an increase in industrial sectors like agro, food, paper, and pulp industries. These industries generate hazardous waste, primarily organic, which is often dumped or processed into the environment. These wastes contribute to contamination, resulting in increased mortality rates and physical and morphological changes in organisms and animals exposed to them (Gaur et al., 2020).

d) **Municipal waste:** Municipal wastes are generated from various municipal activities such as road construction, public facilities, buildings, railway lines, street cleaning, and landscaping. Municipal Solid Waste (MSW) encompasses household waste, commercial and market area waste, slaughterhouse waste, institutional waste (e.g., from schools and community halls), horticultural waste (from parks and gardens), waste from road sweeping, drainage silt, and treated biomedical waste. However, ineffective management of MSW can lead to severe negative environmental and health impacts, including infectious diseases, land and water pollution, drain blockages, and loss of biodiversity (Kumar and Adnan, 2020).

3.2.2 Classification Based on Type

Based on the physical, chemical, and biological characteristics, wastes are classified mainly into two types: biodegradable and non-biodegradable wastes.

i) **Biodegradable wastes:** The residual materials comprising organic substances that undergo decomposition from intricate to straightforward compounds are referred to as these wastes. This category encompasses items such as paper, fabrics, timber, food remnants, as well as fruit and vegetable skins. They originate from a spectrum of human endeavors spanning domestic, industrial, and commercial domains (Pushpakalambiga, and Jasmine, 2021).

ii) **Non-biodegradable wastes:** This category of wastes comprises primarily inorganic materials, some of which are recyclable. Examples include plastic waste, glass waste, cans, metals, and similar items (Pushpakalambiga, and Jasmine, 2021).

These wastes can further be categorized under different types of wastes as follows:

a) **General garbage:** Garbage encompasses the waste generated during the production, sale, preparation, handling, export, and disposal of various materials and items. This includes both solid and liquid waste that may emit an unpleasant odor. Additionally, it attracts various pests such as rats and pigs, necessitating prompt attention for efficient time management. Therefore, solid garbage refers to the undesired, harmful, and discarded substances resulting from everyday civic activities. Managing solid waste involves the systematic handling of its generation, storage, collection, transportation, treatment, and disposal (Shweta Choudhary, 2019).

b) **Street waste:** Public spaces, such as parks, pedestrian zones, and sidewalks, generate a significant and often overlooked waste stream. This waste encompasses a variety of materials, including coarse dirt, dust, fallen leaves, plastic packaging, and beverage containers (Kladnik et al., 2014).

c) **Plastic waste:** Plastics are manufactured through biochemical processes such as polymerization or polycondensation. However, the improper handling of post-consumer plastic waste can have severe environmental consequences. Many everyday items, such as shopping bags and water bottles, are made from plastic and are often used and discarded after a single use. This prevalence of single-use plastics contributes significantly to global environmental pollution and requires urgent attention (Evode et al., 2021).

d) **Farm waste:** Farm wastes, akin to agricultural wastes, pose a significant challenge regarding the management of agricultural soil and groundwater contamination, presenting a crucial issue for agricultural planners. Furthermore, the majority of agricultural wastes represent valuable resources that should be recycled, utilized for industrial applications, and considered for energy recovery (Seadi & Nielsen, 2004).

e) **E-waste:** The excessive reliance of humans on electronic products has led to the escalation of electronic waste (E-waste), which is growing at a rapid rate of 20-25% annually. This accelerated growth is attributed to factors such as market diffusion, replacement cycles, and high obsolescence rates, making E-waste the fastest-growing waste stream (Mor et al., 2021). Additionally, E-waste is a significant global concern due to its environmental and health impacts resulting from the presence of toxic metals and chemical substances (Yong et al., 2019).

f) **Nuclear waste:** Different types of nuclear waste generated from nuclear power plants during weapon manufacturing, experiments, and testing fall into the category of nuclear waste. It is imperative to effectively manage nuclear waste to ensure the safe and sustainable utilization of nuclear energy, spanning from large-scale applications in power generation to various smaller-scale uses in medicine, industry, and agriculture (Petrov et al., 2023).

g) **Hazardous wastes**: Hazardous wastes refer to substances that are no longer required and hold no current or perceived value at a specific time or location. Many materials utilized or generated in chemical processes possess hazardous properties. The primary sources of hazardous wastes encompass industrial, medical, and household wastes, existing in solid, liquid, or gaseous forms. These wastes are categorized and/or possess inherent chemical and physical characteristics such as toxicity, ignitability, corrosiveness, and reactivity. Effectively managing hazardous wastes is crucial for human, economic, social, and environmental health (Zangina & Ali, 2021).

h) **Medical/clinical wastes:** The waste generated from healthcare facilities like hospitals, clinics, surgical theaters, veterinary hospitals, and laboratories is known as medical/clinical waste. This category encompasses surgical equipment, pharmaceuticals, blood, body parts, wound dressings, needles, and syringes (Lee & Lee, 2022).

4. WASTE MANAGEMENT

Waste management encompasses the processes of collecting, transporting, and disposing of sewage, garbage, and various waste products. It is also known by alternative terms such as waste disposal, garbage disposal, and recycling. A comprehensive definition of waste management includes activities such as collecting, destroying, and properly disposing of waste materials (Amasuomo & Baird, 2016). The challenge of managing waste has been apparent for over four millennia, evolving from mere disposal into the pursuit of an integrated waste management approach aimed at minimizing impacts on the biosphere (S. Syed, 2006).

5. ENVIRONMENTAL SUSTAINIBILITY

Environmental sustainability is a crucial approach focused on preserving the delicate equilibrium of Earth's ecosystems while fulfilling the requirements of present and future generations. It entails the responsible utilization of natural resources to minimize environmental impact and ensure their availability for the long term. This concept encompasses various aspects such as reducing carbon emissions, conserving biodiversity, promoting renewable energy sources, and reducing waste production (Unegg et al., 2023).

Moreover, it involves establishing boundaries on four key activities that govern the scale of the human economic subsystem: the use of renewable and nonrenewable resources on the supply side, pollution, and waste absorption on the demand side (Ahmed et al., 2019). Ultimately, it is defined as meeting the needs for resources and services of current and future generations without compromising ecosystem health (John Morelli, 2011). Recognizing the urgent necessity of refining waste management practices is crucial for mitigating associated risks and advancing environmental sustainability (Abila & Kantola, 2013, Nigeria).

Achieving environmental sustainability necessitates a comprehensive approach involving individuals, communities, businesses, and governments. It requires a shift in mindset towards adopting practices that prioritize environmental conservation and social responsibility. Education and awareness play a central role in developing a deeper understanding of the interconnectedness between human actions and the environment, encouraging informed choices that contribute to sustainability. Policy frameworks and international agreements are also vital in establishing targets, standards, and regulations that promote sustainable development and hold stakeholders accountable for their environmental impact. Ultimately, a collective effort toward environmental sustainability is essential for safeguarding Earth's natural resources and ensuring a viable planet for future generations (Eneji et al., 2019).

6. WASTE MANAGEMENT AND ENVIRONMENTAL SUSTAINABILITY:

Effective waste management is a critical resource for achieving environmental sustainability in the future. Electronic waste, transitioning to a circular economy, plastic waste management, bio-based waste management, lifecycle assessment, ecological impacts, and construction and demolition waste are key factors contributing significantly to environmental sustainability (JeyaSundar et al., 2020). In the Swedish waste management system, the most crucial environmental impact categories are climate change, human toxicity, and resource depletion. Emissions of fossil CO2 from waste incineration remain a major source of environmental impacts in these scenarios (Arushanyan et al., 2017). Urban local authorities face significant challenges in establishing efficient solid waste management systems, including environmental sustainability and financial viability (Vuppaladadiyam et al., 2024). Furthermore, certain circular economy policies may lead to minor environmental gains that could be offset by rebound effects or changes in social behavior (Camana et al., 2021).

The environmental sector emphasizes that rapid urbanization has led to a surge in construction activities worldwide, both in developed and developing nations. Consequently, there has been a significant increase in construction and demolition waste, resulting in adverse impacts on urban sustainability. This situation affects economic values and environmental safety, posing serious challenges to urban survival. The extensive urbanization has spurred a substantial rise in construction activities globally, leading to a significant increase in construction and demolition waste. This waste has had negative and potentially fatal impacts on urban sustainability, affecting economic values and environmental safety (Aslam et al., 2020). Moreover, the key obstacles hindering sustainable construction and demolition waste management practices include a lack of awareness, insufficient commitment, ineffective management, limited collaboration, a lack of national vision, inadequate funding, limited infrastructure, insufficient supervision, and weak legal enforcement (Negash et al., 2021).

The primary issue in developing countries stems from population growth and rapid economic expansion. There is a pressing need to revamp the municipal solid waste management system, promote campaigns for improved waste segregation at the source, and enhance the infrastructure of scavengers' associations (Poletto et al., 2016). Inadequate practices in solid waste collection and management can lead to significant urban, sanitary, and environmental challenges such as foul odors, insect proliferation, and groundwater contamination, along with increasing the involvement of waste pickers in urban areas and landfills (Mor et al., 2006). The absence of clearly defined strategies for effectively managing solid waste can result in waste accumulation in developing countries, posing serious environmental risks to communities (Ibrahim & Mohamed, 2016). Moreover, rapid population growth, especially in low-income and middle-income countries, is a major driver of waste generation (Yong et al., 2017). Areas with a higher proportion of female population exhibit lower municipal solid waste per capita and a higher recycling rate, whereas a higher share of senior citizens in the population is associated with lower municipal solid waste per capita but higher gross domestic product and educational attainment, leading to greater municipal solid waste per capita and lower recycling rates (Kenichi Shimamoto, 2019). Waste compositions in these areas are predominantly organic waste, paper, plastic, glass, and metal (Thaniya Kaosol, 2009). However, rising income levels, unchecked urban expansion, and changing lifestyles have contributed to increased consumption of paper, plastic, and other non-biodegradable materials (Vuppaladadiyam et al., 2024). Improper waste handling practices pose serious health and environmental risks (Rinnie Mahajan, 2023; Priya Gupta, 2023).

7. ENVIRONMENTAL CONSEQUENCES OF INADEQUATE WASTE MANAGMEENT

Improper waste management practices, such as open dumping and burning of waste, pose severe environmental and health risks with significant consequences. These practices are widespread in many countries and have led to severe forms of air, water, and soil pollution. Municipal Solid Waste pollution has increased mortality and morbidity rates for various diseases. The release of toxic chemicals and pollutants into the air, soil, and water sources can result in respiratory illnesses, cancers, and other chronic health conditions. Stagnant water in waste areas creates a breeding ground for cholera and vector-borne diseases like malaria and dengue (Rinnie Mahajan, 2023).

According to the World Health Organization (WHO), poor waste collection contributes to environmental and marine pollution, including blockages in water drains. Globally, more than 2 billion tonnes of Municipal Solid Waste are produced each year (Compendium of WHO and Other UN Guidance on Health and Environment 2022, 2022). Solid and liquid wastes from animal and domestic sources can significantly contaminate drinking, irrigation, recreational water, and other water sources in both rural and urban areas. Open dumping and waste in drains cause numerous problems, including emissions of carbon monoxide, particulate matter, nitrogen oxides, and sulfur oxides, leading to atmospheric pollution. Waste dumped in stormwater drains also pollutes water, affecting local land and groundwater quality. During rainfall, leaching of wastewater from landfill sites contaminates groundwater, altering its chemical properties and posing a threat to agricultural and domestic use in surrounding areas (S. Syed, 2006).

Some of the main consequences of the environmental sustainability because of inadequate waste management are as follows:

7.1 Water Pollution

The disposal of solid wastes and wastewater into surface water bodies, such as streams and rivers, along with unsanitary disposal of municipal solid waste at landfills, can lead to significant environmental pollution (Alam & Ahmade, 2013; Giusti, 2009). Municipal solid waste typically contains a high water content, and when surface water infiltrates it, contaminated leachate is produced due to chemical and biological reactions within the landfill. This leachate, which contains a variety of toxic substances, poses a serious threat to soil and water pollution around the landfill. Additionally, volumes of 400–600 liters of leachate are released per ton of waste, which can have detrimental effects on water and soil quality. Therefore, controlling waste leachate in landfills is critically important for both health and environmental protection (Aziz & Amr, 2015; Qasim & Chiang, 2017).

7.2 Soil Pollution

The disposal of municipal solid wastes, the application of fertilizers and chemical pesticides, and the discharge of wastewater from various industries and factories often lead to direct contamination of soil and water environments (Kah et al., 2012). Soil pollution directly affects regional water quality by introducing chemical and microbial contaminants (T.G. Townsend et al., 2012; Christopher J. Rhodes, 2018). Additionally, heavy metals such as mercury, lead, cadmium, and arsenic can accumulate in compost, subsequently reducing the growth of plants and crops when introduced to the soil (Kah et al., 2012). Moreover, non-decomposable plastic materials disrupt soil climate exchange and impede the activity of soil organisms (T.G. Townsend et al., 2012; Christopher J. Rhodes, 2018).

7.3 Air Pollution

The accumulation of municipal solid waste in the environment, particularly waste containing large amounts of organic matter, produces an unpleasant odor due to decomposition, especially during hot seasons (Adeniran & Bello, 2019). Spontaneous and incomplete combustion of waste in the environment also releases various gases into the air. The burning of municipal solid waste containing plastics emits gases such as CO, CH4, H2S, CO2, and dioxin, which are hazardous and contribute to air pollution (Perez, 2006). Additionally, gases produced from aerobic and anaerobic fermentation in landfills include cyclic hydrocarbons, CO, CH4, H2S, CO2, trichloroethylene, chlorobenzene, toluene, tetrachloroethylene, ethylbenzene, and dichloroethane (Dehghani & Karri, 2021). Moreover, the emission of hazardous gases like methane and carbon dioxide significantly contributes to climate change (Abila & Kantola, 2013).

8. ENGINEERING STRATEGIES FOR SUSTAINABLE WASTE MANAGMENET

Some of the main and most effective engineering strategies for sustainable waste management are as follows:

8.1 3R (Reduce, Reuse, Recycle)

The three R's—Reduce, Reuse, and Recycle—form the foundation of sustainable waste management. By minimizing waste production, reusing materials, and recycling, we can conserve natural resources, reduce pollution, and decrease the amount of waste sent to landfills (Rania Shatnawi, 2018).

8.2 Recycling

Recycling plays a crucial role in waste management and is essential for creating a more sustainable future. It encompasses the collection, processing, and transformation of waste materials into new products, thereby reducing the demand for new materials and decreasing waste disposal in landfills. Common recyclable materials include paper, cardboard, plastic, glass, metal, and electronic waste. These materials are collected, sorted based on their composition and quality, and then processed to create new products (Rania Shatnawi, 2018).

8.3 Waste-to-Energy: Using Waste as Fuel for Energy Production

Waste-to-energy technology involves converting municipal solid waste or garbage into electricity or heat. This waste includes various materials such as biogenic products (plant or animal-based) like paper, cardboard, food waste, grass clippings, leaves, wood, and leather goods. It also includes non-biogenic combustible materials such as plastics and other synthetic materials derived from petroleum, as well as non-combustible materials like metals and glass. Waste-to-energy technologies are beneficial as they reduce waste volumes, environmental impacts, health risks, and reliance on fossil fuels for power generation (Kumar et al., 2019).

Adopting waste-to-energy systems can help mitigate the adverse environmental effects of waste generation by producing renewable and sustainable energy, contributing to a circular economy. This approach can reduce waste volume, minimize environmental impacts from waste disposal, and generate renewable energy. For instance, the US Energy Information Agency (EIA) estimated that in 2021, 64 power plants in the United States produced about 13.6 billion kilowatt-hours of electricity by burning approximately 28 million tonnes of combustible Municipal Solid Waste (Alao et al., 2022).

8.4 Waste reduction

Waste reduction is a critical element of waste management essential for creating a more environmentally friendly future. It focuses on minimizing the quantity of waste generated initially, rather than solely dealing with its management and disposal afterward. Through waste reduction, we can conserve natural resources, decrease pollution, and promote sustainability. Effective strategies for waste reduction include minimizing packaging, utilizing reusable products, and avoiding single-use items (Rania Shatnawi, 2018).

8.5 Waste Landfill

Landfills have been in use for centuries and remain the most prevalent method of waste disposal globally, despite efforts to promote recycling and reuse of waste materials (Iyenoma ThankGod Osazee, 2021). There are two main types of landfills crucial for proper waste disposal. Firstly, Sanitary/secure landfills: These landfills are typically located in areas where natural features act as barriers between the landfill and the surrounding environment. Additionally, they incorporate various safety measures into their design to minimize disposal risks. Secondly, Secure landfills: These are designated facilities authorized to accept toxic waste, and they adhere to significantly stricter safety precautions compared to standard sanitary landfills.

8.6 Waste Disposal

Waste disposal continues to be an important waste management solution, playing a significant role in promoting environmental sustainability. However, when characterized by a lack of proper treatment processes and open dumping, this method poses growing public health risks to human lives, animals, and plants (Abila & Kantola, 2013, Nigeria). Inappropriate disposal of solid waste can have serious adverse impacts on both the natural environment and human health within society (Rania Shatnawi, 2018).

8.7 Thermal Treatment

Thermal treatments such as incineration and pyrolysis/gasification are considered superior solutions for waste treatment. Incineration involves burning waste in the presence of oxygen at high temperatures, resulting in the release of gases, ash, and thermal energy (Zaman, 2009). This technology is used to destroy solid waste through controlled burning at elevated temperatures (Rahman and

Alam, 2020). Waste incineration, being a high-temperature oxidation process, plays a crucial role in safe waste disposal. It offers several benefits including minimal environmental pollution, reduced waste volume, complete waste neutralization, and the potential for reuse of thermal energy. Advanced incinerator technology can effectively handle all types of waste, addressing the increasing challenges of waste management amidst population growth and rising consumption, thus contributing to a cleaner environment (LUP et al, 2018).

9. CONCLUSION

Sustainable waste management is vital for environmental sustainability, tackling solid, liquid, and gaseous waste challenges. This includes managing solid waste types like urban, industrial, agricultural, biomedical, and radioactive waste, which pose environmental risks due to non-degradability. Liquid waste must be managed to prevent water pollution, while gaseous emissions contribute to air pollution and climate change. Tailored management strategies are needed based on waste source classification, distinguishing between biodegradable and non-biodegradable waste for suitable disposal and recycling. Effective waste management practices include segregation, recycling, treatment, and proper disposal to mitigate risks and ensure public health safety, especially for hazardous waste.

A holistic approach involving individual actions, community engagement, corporate responsibility, and governmental policies is crucial for sustainable development. Best practices in waste management reduce environmental footprints, while improper practices release toxic pollutants, necessitating effective waste management to foster a healthier environment amidst urbanization and economic growth challenges.

In conclusion, sustainable waste management is essential, requiring comprehensive strategies, robust regulatory frameworks, and collective engagement to mitigate pollution, preserve resources, and ensure a healthier planet.

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