Deltas of the World

Mahmoud Nasr
Balasubramani Ravindran *Editors*

Solid Waste Management in Delta Region for SDGs Fulfillment

Delta Sustainability by Waste Management

Springer

Deltas of the World

Series Editor

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Worldwide, over 600 million people live in deltas. Extensive human activities in deltas, their supplying rivers, and related maritime currents increase the pressure on deltas' natural resources and habitat equilibrium, leading to degradation of the available resources and jeopardizing inhabitants' livelihoods – and in some cases even their lives.

This book series is intended to promote a sustainable future for deltas around the globe and the communities that live in them. Accordingly, we publish studies focusing on various aspects of deltas, including hydrogeology, soil pollution, water pollution, environmental hydrology, environmental hydraulics, groundwater engineering and management, morphology, anthropology, socioeconomics, wastewater management, water resources engineering and management, agriculture, greenhouse agriculture, irrigation and drainage engineering, hydraulic structures, geophysics and geology, sedimentology, mineralogy, remote sensing and GIS studies, climate change variabilities and impacts, marine-delta interactions and sustainability, and solid waste management. The findings presented here support the SDGs and Agenda 2030 with regard to helping countries with deltas and related environments to preserve their natural resources for future generations.

The editors invite scientists, researchers and scientific communities to contribute to the series by submitting delta atlases, edited books, monographs, and high-quality conference proceedings focused on deltas around the world.

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1 Solid Waste Management and Sustainability in Deltas: Introduction and Updates

Mahmoud Nasr

Abstract

Deltas, comprising approximately 5% of the Earth's land surface, occupy a high population density globally. The distribution of population density depends on the geographical location and the countries or regions of Deltas under investigation. Each Delta is unique and influenced by specific hydrological, geological, and environmental conditions. Deltas face the pressing need for effective waste management strategies to mitigate environmental degradation and health risks. This chapter is an introduction to the critical nexus of solid waste management (SWM) and sustainability in Deltas, shedding light on the corresponding challenges and barriers. The chapter's main findings would strengthen the contribution of stakeholders, policy-makers, and private and public sectors in achieving sustainable SWM strategies.

1.1 Introduction

A river delta refers to the area of land formed at the mouth of a river where the river splits into several channels (i.e., a landform shaped like a triangle) (Elsadek et al. 2024). They are characterized by a network of distributaries, which are channels that branch off from the main river and distribute its water and sediment into the surrounding area. Deltas

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occupy urban areas, industries, infrastructure, farmlands, and aquaculture ponds (Youssef et al. 2024). The compacted sediment layers of Deltas can be used to extract hydrocarbon (natural gas, oil, and coal) and harvest salts, providing crucial economic significance to the country. Table 1.1 lists the major Deltas worldwide.

During the past decade, most of the world's Deltas experienced severe pollution from various anthropogenic practices associated with illegal solid waste disposal (Deng and Liu 2024). There is a great interest in understanding the interaction of physical, ecological, and social variations within delta systems in relation to human waste disposal. Hence, this chapter discusses the commonly performed reliable waste management practices in Deltas, including (i) implementing separation-at-source initiatives that sort recyclable items into their respective recycling streams, (ii) providing beneficial solutions to the disposal of organic waste materials, such as garden waste, food waste, wood waste, and other manufactured biodegradables, (iii) reducing the percentage of waste that is sent to landfill

Table 1.1 Largest Deltas worldwide and their features

Delta name	Location	Notable features
Ganges–Brahmaputra Delta	India	The largest delta, highly fertile, supports the highest population density
Mekong Delta	Southeastern Asia	Known as the Nine Dragon River Delta, rich in biodiversity, feeds the Vietnamese population
Lena Delta	Russia	Frozen tundra turned lush wetland, supports trade and breeding of fish
Huang He Delta	China	Delta's location changes, engineering to protect oil and gas wells
Mississippi Delta	United States	Cultural significance, shrinking due to rising sea level
Indus Delta	Pakistan	Suffering from loss of vegetation, shrinking mangrove forests
Volga Delta	Russia	Europe's largest delta, vital for migratory birds and fish
Orinoco Delta	Venezuela, South America	Uninhabited, national park with diverse wildlife
Niger Delta	Nigeria, Western Africa	Rich in marine life, historical importance, supports agriculture and fishery
Tigris-Euphrates Delta	Southeastern Asia	Drains rivers across 5 countries, birthplace of civilizations

(a bottom liner and leachate collection system are required), and (iv) promoting a green approach to business and delivering maximum value to our clients.

1.2 Bibliometric Analysis of Solid Waste Sustainability

The bibliometric study analyzes data on the published articles about "Waste", "Sustainability", and "Deltas" searched within the Article title, Abstract, and Keywords. The results were analyzed according to the number of articles per year, journal titles, subject areas, affiliation, country, and citation analysis. The SCOPUS search engine was used in this bibliometric study. Table 1.2 lists the essential parameters and results of this search strategy in the 2010–2023 period. The published articles address the main waste management and disposal, pollution reduction from waste, and the associated toxicological features. The categories of these articles include:

- strategy and management,
- general environmental science, and
- renewable energy, sustainability, and the environment

Subject areas include, but are not limited to:

- sources and occurrences of pollutants related to solid waste generation in the Delta region.
- synergism of contaminant exposure and biological, ecological, and human health impacts.
- contaminants of emerging concerns, such as antibiotic-resistant microorganisms or genes, microplastics/nanoplastics, and electronic wastes (Demarema et al. 2024)
- remediation/mitigation of environmental contaminants via innovative techniques (Dogu et al. 2021)
- modeling of pollution processes, patterns, or trends, demonstrating environmental occurrences, transport, and behavior.
- synthesis/fabrication of novel materials used for remediation and/or mitigation of pollution
- waste management policy, education, economic assessment (Life cycle cost, LCC)), and environmental assessments (life cycle assessment, LCA and social-LCA). For instance, LCA is a method for the environmental assessment of products and services, covering their life cycle from raw material extraction to waste treatment.
- technical, political, and environmental concerns associated with material cycles and waste management.
- studies on eutrophication and secondary pollution by eutrophication caused by the disposal of solid wastes into the aquatic environment

Table 1.2 Bibliometric analysis data on solid waste sustainability in Deltas

Parameter	Data/observation
Database	SCOPUS
Query string	TITLE-ABS-KEY (waste AND sustainability AND deltas)
Period time	Year of publication 2010–2023
Language	English
Number of documents	66 document results
Document type	Article (71.2%) Conference review (10.6%) Conference Paper (9.1%) Review (4.6%) Book Chapter (4.5%)
Top 10 subject area	Environmental Science (34) Engineering (20) Energy (10) Earth and Planetary Sciences (8) Agricultural and Biological Sciences (6) Business, Management and Accounting (4) Computer Science (4) Materials Science (4)
Top 10 journals	IOP Conference Series Earth and Environmental Science (3) Science of the Total Environment (3) Buildings (2) Construction and Building Materials (2) Environmental Pollution (2) Journal of Cleaner Production (2) Water Environment Research (2) Advanced Materials Research (1) Advances in Global Change Research (1) African Journal of Hospitality Tourism and Leisure (1)
Top 5 affiliations	ARENA Research for Sustainable Resources (2) Ministry of Education of the People's Republic of China (2) Nagasaki University (2) RUDN University (2) Chinese Academy of Sciences (2)

(continued)

Table 1.2 (continued)

Parameter	Data/observation
Top 5 countries	China (15) Nigeria (9) United States (8) Egypt (7) Viet Nam (5)
Top 5 funding sponsors	National Natural Science Foundation of China (8) Fundamental Research Funds for the Central Universities (2) Ministry of Higher Education, Malaysia (2) Natural Science Foundation of Guangdong Province (2) Anhui Provincial Department of Science and Technology (1)

The main objectives and aims of these articles are to investigate:

- socio-economic benefits and policy implications of generating sustainable energy from municipal solid waste (MSW).
- tracking the carbon flows in municipal waste management: Paving the Way for Sustainable Development
- resource utilization of drinking water treatment aluminum sludge in green cementing material production.
- landfill site selection for sustainable solid waste management (SWM)
- carbon reduction trade-off between bioenergy generation and that spent on collection, transport, and treatment.
- environmental and economic trade-off-based approaches towards biogas recovery from solid waste.
- the avoidance of the detrimental effects of toxic chemicals and materials on the receiving environmental dimensions (soil, water, and atmosphere)
- sustainability assessment of biofuel and value-added product from organic portion of solid waste (Emmanouilidou et al. 2023)
- valorization of cattle manure via a thermo-chemical process to produce environmentally friendly products (Mannaa et al. 2024)
- sustainable energy recovery from mixed agri-food waste as a feedstock for bio-circular-green economy (Blanchard et al. 2023)
- application of waste biomass for the production of biofuels and catalysts
- life cycle environmental benefits, and technology development and challenges of recycling waste liquor and chemicals in the recovery of bioethanol
- zero-waste approaches for sustainable production and biorefineries of microalgal biomass

Table 1.3 Characterization methods of solid wastes

Characterization method and/or equipment	Role in defining the biomass features
Scanning electron microscope	Scanning electron microscope (SEM) is one of the common methods for imaging the microstructure and morphology of the materials
Energy-dispersive X-ray spectroscopy	It is a method of elemental detection via the collection of characteristic X-rays induced by electron beam radiation
Transmission electron microscopy	It is a technique of imaging the internal structure of solids (etc., morphology, and size) using a beam of high-energy electrons transmitted through the solid
Thermogravimetric analysis (TGA)	Is a powerful technique for the measurement of thermal stability of materials including solid wastes
Fourier transform infrared spectroscopy	It is used to characterize the different functional groups such as lipids, proteins, nucleic acids, and polysaccharides present on the solid waste surface
X-ray photoelectron spectroscopy (XPS)	It is a quantitative technique used to analyze the solid waste surface chemistry, e.g., determining the surface composition (elemental identification)

The chapters' outputs are important for a multidisciplinary and diverse audience of scientists, policymakers, the broad public, and the environment-caring stakeholders.

1.3 Solid Waste Characterization Methods

The proper characterization techniques of this biomass comprise pore-size distribution, ash fusion and deformation temperatures, calorific values, and thermogravimetric analysis (Table 1.3) (Palansooriya et al. 2023). These characterization methods would support the choice of specific biomass for the most appropriate implementation (H_2, CH_4, or ethanol production) (Srimalanon and Kachapongkun 2023).

1.4 Physical, Thermochemical and Biological Waste-to-Energy Conversion Technologies

The unrestricted disposal of solid wastes severely influences the growth and activities of aquaculture and deteriorates the relationships between zooplankton, phytoplankton, and fish (Lopez et al. 2018). The thermo-chemical transformation methods (e.g., pyrolysis, gasification, and combustion) are used to generate syngas, charcoal, and biofuel (Ahmad et al. 2023). These methods are summarized in Table 1.4.

Table 1.4 Typical operating conditions for thermochemical and biological waste-to-energy conversion technologies

Technology	Temperature (°C)	Heating rate (°C/s)	Residence time	Typical product distribution	Note
Incineration	800–1200	Variable	Variable	Bottom ash > Fly ash > Slag > Gas	It is the primary and most conventional thermal waste-to-energy conversion technology (He et al. 2023) Incineration of fossil fuels is considered one of the main sources of GHG emissions into the atmosphere
Flash pyrolysis	800–1000	1000	0.5 s	Bio-oil > Gas > Biochar	Pyrolysis (devolatilization) is the thermal degradation of an organic substance in the absence of air to produce char, pyrolysis oil, and synthesis gas, e.g., the conversion of wood to charcoal Fast pyrolysis of biomass is an endothermic process, where heat is supplied to the biomass for initiating depolymerization at the reaction temperature
Slow pyrolysis	300–700	0.1–1	10–100 min	Biochar > Bio-oil > Gas	Slow pyrolysis is characterized by low temperatures, slow heating rates, and long residence times Slow pyrolysis takes place in a temperature range of 300 °C–550 °C and heating rates of 0.01 °C/min–80 °C/min and has a vapor residence time that can last minutes, hours, or even days
Intermediate pyrolysis	500–600	2–10	10–20 s	10–20 s	In this process, heating rates are significantly lower than in fast pyrolysis and solids residence times are much longer (few minutes)
Liquefaction	250–450	0.05–5	1–40 min	Bio-oil > Tar	For example, coal liquefaction is the process of making a liquid fuel from coal

(continued)

Table 1.4 (continued)

Technology	Temperature (°C)	Heating rate (°C/s)	Residence time	Typical product distribution	Note
Gasification	700–1000	Variable	30–90 min	Syngas > Biochar	It is a high-temperature process in which carbonaceous fuels and organic solid matters are transformed into a gaseous mixture of hydrogen (H_2) + carbon monoxide (CO), called synthesis gas (or syngas) further used as a fuel gas
Anaerobic digestion	35–37	None	Days	Methane > Other gases > Bio-sludge	It is an anaerobic biological process that converts organic matter into biogas, including ≈ 50–70% CH_4, 30–50% CO_2, and trace amounts of other gases, e.g., H_2S, and NH_3
Composting	25–55	–	1–2 months	Humus > Nutrients > Minerals	It is a treatment process in which the organic constituents of biosolids are biologically decomposed under controlled aerobic conditions (Isibika et al. 2023)

1.4.1 Physical-Based Conversion Using Cavitation

Cavitation-based technologies can be employed to improve the anaerobic digestion (AD) efficiency, maintaining sustainable management of solid wastes (e.g., food wastes and agricultural residues) (Sonu et al. 2023). In this process, the liquid state is rapidly transformed into the gaseous state as an action of growth and collapse of bubbles. The creation of cavitation bubbles in the liquid phase results in the generation of intense shock waves with tremendous destructive forces. The efficiency of the cavitation process performance is influenced by vapor pressure, viscosity, temperature, surface tension, the existence of dissolved gases, and the presence of other components, such as surfactants. Some physical (mechanical) factors, e.g., shock waves, microjets, and shear stress, also affect the completion of the cavitation process (e.g., lignin depolymerization). Cavitation is classified into hydrodynamic cavitation, vaporous cavitation, gaseous cavitation, and vibrational cavitation, so-called acoustic cavitation according to the conditions of formation and development of cavitation bubbles. The collapse energy of cavitation bubbles destroys material structure, further affecting material characteristics (e.g., particle size, specific surface area, and porosity). The modification in these features facilitates lignocellulosic biomass solubilization as well as biogas productivity. The success of particles' disintegration by cavitation depends on the efficient breakdown of the hydrogen bonds, Van der Waal forces, and covalent bonds of the complex waste structure, further generating simpler byproducts (high-value aromatic monomers) soluble in the medium. The extremely high temperatures and pressures accompanied by cavitation can create a series of chemical reactions, yielding multiple reactive species.

1.4.2 Biological-Based Conversion

1.4.2.1 Anaerobic Digestion

Anaerobic digestion (AD) is a sustainable management technique employed to convert the organic fraction of solid wastes and agricultural feedstock (e.g., crop residue and cattle manure) into biogas and digestate (Wang et al. 2023). Biogas can be used to generate fuel for vehicles, electricity, and heat, whereas digestate can be employed for producing fertilizers, and composts (Midden et al. 2023). This step is crucial to reduce the landfilling of these organic wastes that are responsible for greenhouse gas (GHG) emissions, and can reduce the value of the surrounding areas and cause soil and water contamination (Heidari-Maleni et al. 2023). In particular, integrating AD into government policies to treat organic wastes would assist developing countries in providing direct financial returns and maintaining environmental conservation. The advantages of this system include the treatment of wastes with lower energy consumption, and less sludge production compared to aerobic-based bioprocesses. However, the disadvantages include the requirement of further treatment to meet discharge standards, insufficient N and P removals, and a higher sensitivity to environmental conditions (temperature and medium pH) fluctuations. However, the absence of expertise in AD technology to design, construct, and operate the technology may delay the biogas production project.

1.4.2.2 Composting

Microorganisms perform multiple bio-reactions to facilitate the biological decomposition of biodegradable solid waste under an aerobic condition, describing the composting process (Mengqi et al. 2023). This process yields a compost material rich in nutrients, minerals, and beneficial microorganisms called humus, which can be used to replace chemical fertilizers for crop production (Blanchard et al. 2023). In this process, black soldier fly larvae (*Hermetia illucens*) can sufficiently utilize various types of organic wastes (animal meat and seafood wastes), maintaining a cradle-to-cradle system, where the waste is effectively managed and converted into useful resources (Syarifinnur et al. 2023). However, composting is a slow process because not all organics are readily biodegradable and suitable for composting. The composite material should be free of damaging components, metal ions, and emerging contaminants to avoid the spreading of diseases (Md et al. 2023).

1.4.2.3 Vermicomposting

Vermicomposting is a process that describes the degradation of organic wastes by the action of earthworms together with microorganisms, causing recovery of a humus-like material called vermicompost. The main advantages of vermicomposting include the reduction of the waste volume and stabilization of the organic solid residues (Chowdhury and Sarkar 2023). However, vermicomposting requires an extended period (a treatment period of over six months) to convert the organic matter into usable forms. Moreover, vermicomposting is not efficient in killing pathogens and it releases a very foul and unpleasant odour (Zhang et al. 2023).

1.4.3 Thermal-Based Conversion

1.4.3.1 Combustion

The combustion process expresses the burning of biomass in the presence of an air supply, generating heat energy along with CO_2 and water (Yadav et al. 2023). Direct combustion utilizes the heat energy of combustion reaction to produce the steam to run the turbine compressor or pump; i.e., a mechanism recognized as heat-to-mechanical energy. However, this process might suffer from the creation of some environmental concerns associated with the release of CO_2, NO_x, SO_x, and H_2S emissions (Tawfik et al. 2024). As such, the operating factors of the combustion process should be optimized using precise numerical models and simulations to avoid the creation of the GHG effect problems (Mohod and Bagal 2023).

1.4.3.2 Incineration

Incineration is used to convert the waste materials into incinerator bottom ash, clinker, fly ash, and particulates, further reducing waste volume (Chen et al. 2023). The released ash can be used as a partial replacement for cement in concrete mixes (e.g., a supplementary cementitious material) because it contains some quantities of typical cement minerals. The incineration process is also used to eliminate pathogenic organisms and harmful toxic substances (Arteaga et al. 2023). The generated emissions (SO_x, NO_x, and CO_2) should be controlled to avoid air pollution (Halba et al. 2023).

1.4.3.3 Gasification

Gasification describes a thermochemical process used to convert solid waste rich in carbonaceous matter into fuel gases or syngas under a controlled amount of oxygen and/or steam (Chang et al. 2023). Water and tar are also generated as unwanted products from the gasification process. The produced syngas, containing a mixture of carbon monoxide (CO), hydrogen (H_2), and traces of methane (CH_4), can be utilized directly as fuels for engines and turbines. The variation of the generated byproduct amounts depends on the temperature applied, ranging between 700 and 1300 °C (Ahmad et al. 2023). The accomplishment of solid waste gasification also relies on the type of gasifying agents, such as air, oxygen, steam, or supercritical water inside a gasifier (Chu et al. 2023).

1.4.3.4 Pyrolysis

Pyrolysis is a thermal treatment method, where the solid waste is heated under an oxygen-deprived condition at temperatures ranging from 500 to 800 °C (Hasan et al. 2023). This process tends to generate liquid, solid, and gaseous substances based on the pyrolysis temperature applied, e.g., slow pyrolysis (300 °C ~ 700 °C; <1 °C/s), fast pyrolysis (450 °C ~ 800 °C; 300 °C/min), and flash pyrolysis (>600 °C; 1000 °C/s). However, most studies used the pyrolysis process to convert solid wastes into biochar rich in carbon (Ezz et al. 2023), where this material can be employed to restore contaminated soils, enhance crop production, and mitigate the risk of GHG emissions (e.g., CO_2, CH_4, and N_2O) in farmland (Ganesan et al. 2023). Rotary kilns, microwave reactors, and screw kilns are robust and affordable units used to perform the pyrolysis of tires, complex plastic, electronic and electric materials, and wood waste (Carregosa et al. 2023).

1.5 Advantages and Challenges of Biochemical Conversion Processes

Waste-to-energy (WtE) is one of the most important technology considerations for the sustainable management of waste. Biochemical conversion technology defines the microbial degradation and breakdown of the organic portions in solid wastes, including (e.g., food/kitchen residues, agricultural crops, and cattle manure). The main advantages and drawbacks of this technique are summarized in Table 1.5. Anaerobic digestion utilizes microorganisms to convert biodegradable and moist waste (biomass) such as food waste and livestock sludge into biogas (Eraky et al. 2023). The biogas (methane) produced in the anaerobic biological process is a mixed gas, and its main contents are CH_4, CO_2, H_2S, and water. This process can be used for biogas recovery and generation of nutrient-rich digestate (Midden et al. 2023).

Composting denotes an aerobic method of decomposing organic solid waste. It is a major type of recycling organic waste to produce useful fertilizers. In this process, biological decomposition of organic materials occurs under aerobic conditions with part of the process conducted under thermophilic (>50 °C) conditions (Nanda et al. 2023). Microorganisms play a significant role in this process by bio-transforming contaminants into less hazardous components and immobilizing pollutants.

Phycoremediation (microalgae-based wastewater treatment technology) is used for removing nutrients from wastewater while generating biomass that can be a substitute energy source replacing conventional feedstock. Algal biomass can also be processed to prepare a wide range of chemical and bio-medical products.

Table 1.5 Advantages and disadvantages of biochemical conversion processes

Biochemical processes	Advantages	Disadvantages
Composting	• Low cost, and consumes less resources (e.g., energy and water) • Used to make fertilizers (e.g., composts) • Protects soil against erosion • Increases nutrients in soil	• Extended time of microbial adaptation • Requires more land area • May need nutrient supplementation before compost utilization • Possibility of contamination by heavy metals
Vermicomposting	• Improves water holding capacity • Supply various micro and macronutrients to agricultural lands • Protects soil from erosion	• Proper growth conditions for worms should be maintained
Anaerobic digestion	• Simple operation • Less maintenance • Reduce biochemical oxygen demand (BOD) concentrations using a low-cost method • Biogas production	• Energy requirement to maintain mesophilic methanogenic process • Acidification may occur due to volatile fatty acids accumulation at higher organic loads
Landfilling	• Easy to deal with waste • Cheap way to get rid of the waste when land is available • Prevents illegal solid waste dumping	• May pollute the soil (e.g., leas to deforestation) • Contributes to groundwater pollution • Leads to ecological imbalance

1.6 Meeting SDGs from "Waste-to-Energy" Strategy

The "waste-to-energy" strategies aim at transforming non-recyclable waste materials into valuable energy forms (e.g., heat, electricity, and fuel) (Aboughaly and Fattah 2023), achieving a sustainable waste management approach (see Table 1.5) (Santulli et al. 2023). These techniques include incineration, gasification, decarbonization, combustion, pyrolysis, AD, and landfill gas recovery. The implementation of these emerging SWM methods would assist in fulfilling the targets of the sustainable development goals (SDGs) (Shea and Thornton 2019).

1.6.1 SDG1: No Poverty

Energy generated by waste management is consumed by individuals and society worldwide for adopting several human-related activities (e.g., transportation, manufacturing, lighting, heating, cooling, standby power) (Manjunath et al. 2023). For example, almost every institution in society, e.g., schools, workplaces, offices, universities, and colleges, requires electricity. Nations and communities (e.g., connection between researchers and policymakers) employ the waste management practice to fulfill their energy requirements to perform their duties (Target 1.1) (Banik et al. 2023). Several job opportunities can be created by establishing waste-to-energy conversion projects (Target 1.4), further reducing the unemployment rate trend (Piske et al. 2023). In Malaysia, the design, establishment, and operation of energy recovery facilities using wastes as an input feedstock have created jobs for the local community (Noor et al. 2013). Stakeholders can work towards reducing people living in poverty by considering economic profit, ecological costs, and social benefits from sustainable waste management (Target 1.A).

1.6.2 SDG2: Zero Hunger

Several issues worldwide, such as pandemics, wars, and inflations, have recently participated in reducing the quantities of available natural resources (e.g., natural resources include a wide array of categories, e.g., agricultural, conservational, forestry, oceanic, water, energy, and mineral resources). This situation adversely impacts the food security status of developing and poor countries (Heiba et al. 2023a). The management of organic wastes contributes to food production via several routes, including the implementation of the pyrolysis process to produce biochar used to enhance the soil's physical properties (Target 2.3). Moreover, the composting of organic waste feedstock has been employed to produce organic fertilizer used for increasing crop yields (Czekała et al. 2023). This management method also minimizes the spreading of illegal waste dumping and landfilling sites (Akhtar et al. 2023). Biochar can also be used as an active component in food processing and packaging applications (Target 2.5), further addressing various emerging ecological challenges (Podder et al. 2589). For instance, biochar is required for producing alcoholic beverages (Target 2.B), and decolorizing fruit juice and sugarcane syrup (Fang et al. 2023). Biochar was also successfully employed to improve the quality of sheep manure composts and reduce N_2O, CH_4, and NH_3 emissions by 68.64%, 65.23%, and 42.05%, respectively (Wang et al. 2023a).

1.6.3 SDG3: Good Health and Wellbeing

Inappropriate management of solid wastes, especially wastes from pharmaceutical industries, is responsible for secondary pollution, such as air and soil pollution (Sapkota and Pariatamby 2023). The unmanaged and uncontrolled solid waste disposal sites disturb public health and negatively affect the quality of life of all individuals. Some of the diseases and drawbacks associated with illegal solid waste disposal include anemia, mental disorders, nausea/vomiting, inhalation injuries, and leukaemia (Awino and Apitz 2023).

The management of electrical and electronic waste is essential to avoid the endangering of human health (e.g., a rise in blood pressure and irritation of the eyes, skin, and lungs), causing thousands of deaths annually (Target 3.2). Most of these concerns accompanied by solid waste pollution can be avoided using sustainable, eco-friendly (Target 3.3), and cost-efficient biological and thermo-chemical waste management processes (Dar et al. 2023). Establishing well-designed landfill sites (these sites should not be placed within surface water or water resources protection areas), as well as implementing waste recycling plants and infrastructure, is crucial in reducing the negative impacts of waste on both the environment and human health (Target 3.5).

1.6.4 SDG4: Quality Education

Ensuring high-quality education is an essential strategy of SWM, providing equitable education for boys and girls (Target 4.1). Developing waste management programs can support the awareness and behavior in low-income countries that suffer from the health impact of solid waste disposal (e.g., waste dumping in unauthorized locations) (Heiba et al. 2023b). High-quality teaching can be ensured by involving trainees (men and women) in the learning processes for waste sorting and recycling (Target 4.3). Knowledge transfer (sharing) is essentially required to overcome the limitations accompanied by insufficient resources, grants, or facilities used to employ waste recycling projects (Uba et al. 2023).

1.6.5 SDG5: Gender Equality

Energy is one of the main human needs, influencing the types of activities performed by men and women (Wang et al. 2023b). For instance, the waste recycling habit assists women who face great challenges in transferring household and domestic wastes to disposal sites. Moreover, waste management facilitates the women's work to pick recyclable waste from bins, followed by the sorting and processing wastes at plastic and organic waste recycling facilities. Agricultural waste management plays a vital role in the economic stability of smallholder women farmers by reducing reliance on external markets, lowering expenses, and generating additional income through the sale of crop residues in local markets (Target 5.A). It's important to ensure women's active participation and equal opportunities in establishing effective waste management projects (Ansari et al. 2023). Women should be involved in higher-income and decision-making positions in the sustainable waste sector, supporting the gender-waste management nexus (Target 5.5).

1.6.6 SDG6: Clean Water and Sanitation

Dumping large quantities of solid wastes, e.g., hospital, medical, and healthcare wastes, into the aquatic environment negatively affects the surface water (streams, rivers, and lakes) quality (Palansooriya et al. 2023). Waste management is crucial for avoiding the deterioration of water resources because the recent population growth (Peng et al. 2023), urbanization, and socioeconomic development have increased the industrial and domestic water demand (Target 6.1). Moreover, this waste management pattern tends to save water needed for food production, and reduce groundwater contamination from landfills and industrial reservoirs (Target 6.6) (Dadebo et al. 2023a). To achieve sustainable freshwater production (Saqr et al. 2024), SWM and soil and wastewater remediation should be considerably improved (Target 6.3) (Aboughaly and Fattah 2023).

1.6.7 SDG7: Affordable and Clean Energy

Different forms of energy can be produced from the thermochemical treatment of solid wastes. These treatment technologies include (i) gasification to produce syngas and ash/slag (mineral residues), (ii) pyrolysis to generate liquid fuel (bio-oil), and (iii) combustion to obtain power and heat (Target 7.1) (Hasan et al. 2023). Biogas recovery from the AD of organic wastes can produce electricity and heat or as an energy source for cooking (Target 7.2) (Subbarao et al. 2023). Waste management offsets are a specific type of carbon footprint and used to eliminate and avoid CO_2 emissions because the projects (thermal treatment of solid waste) either capture emissions from waste or reduce the total amount of waste (Target 7.3) (Aboughaly and Fattah 2023). As such, carbon credits represent the difference between how much GHG is created from making the product from raw materials and that obtained when using recycled materials.

1.6.8 SDG8: Decent Work and Economic Growth

Environmental-friendly projects are adopted to raise the growth in employment and income, supporting the green economy concept. New green job opportunities (e.g., environmental engineer, waste collector, and waste management engineer, project manager, and consultant) are generated through implementing the waste recycling facilities (Target 8.2). These job opportunities have recently increased because waste management companies are expanding their services to include recycling, composting, and other environmentally friendly practices (Target 8.3). These practices provide beneficial products, such as bioenergy, bioplastic, organic fertilizer/biofertilizer, and biochar (Sorout et al.

2023). Increasing the number of biogas-producing plants that receive biogenic feedstock has reduced environmental concerns caused by uncontrolled dumping, open-air incinerators, and landfills, promoting sustainable economic growth (Target 8.4).

1.6.9 SDG9: Industry, Innovation and Infrastructure

An integrated dark- and photo-fermentation of organic waste feedstock is used to produce hydrogen gas. This gas is an innovative energy carrier that has several applications in fuel cells to produce electricity, petroleum refining, vehicular transportation, and aerospace (Eraky et al. 2023). Moreover, ethanol production through the fermentation of agricultural and fruit wastes (sugar transformation into carbon dioxide and alcohol typically by yeasts under an anaerobic condition) is progressively attracting investments and inventiveness. Industrial waste management includes segregation, land application (composting), landfill, and recycling of several types of wastes, such as paper, glass, organic, metal, plastics, wood, and grass (Target 9.1). Stakeholders have recently focused on overcoming the techno-economic challenges that can face the success of waste management technologies, including collection and disposal infrastructure, and ineffective recycling or composting (Target 9.2). Other challenges include financial constraints, inadequate technological advances, and a lack of clear regulations and support from localities (Target 9.3). Overcoming these limitations would govern the climate-energy nexus (Bhatia et al. 2023).

1.6.10 SDG10: Reduced Inequality

Equitable resource distribution is one of the main social aims that can be achieved by reducing cities' carbon footprints (Karthik et al. 2023). The international trade of waste between countries is used for further treatment, disposal, or recycling (Target 10.a). Toxic or hazardous wastes are often transferred (exported) from developed countries to developing countries, and they are often disposed of in open landfills or burned in incinerators. People in some developing countries may rationally accept increased exposure to hazardous pollutants in exchange for opportunities to increase their productivity (Ngulube et al. 2024), and, hence, their income. As such, the hazardous waste trade should be regulated (Target 10.3), specifically to prevent the dumping of hazardous waste in the lands of less developed countries. Moreover, the waste recycling projects support the countries that have no many natural resources (e.g., minerals, metals, and forests), or those subjected to natural resource depletion (Target 10.6) (Chowdhury and Sarkar 2023).

1.6.11 SDG11: Sustainable Cities and Communities

People prefer living in urban cities that have proper SWM systems, e.g., collection and transportation, reuse or recycling, and treatment or safe disposal. As such, poorly designed and planned urbanization tends to cause multiple barriers, such as air and water pollution, land degradation, emissions of methane and hazardous leachate, and climate change (Target 11.2). The uncontrolled dumping and accumulation of solid wastes in cities increase land and atmosphere pollution, plant death, loss of habitats, and infection and transmit diseases (Ducasse et al. 2022). The Internet of Things (IoT) technique has been recently employed to maintain a smart garbage monitoring system, showing the garbage status through an IoT application. This approach attempts to optimize resource allocation, reduce running expenses, and improve the sustainability of waste services (Target 11.6). Moreover, using IoT in waste management attempts to provide separate areas, e.g., green and public spaces, and commercial areas, further improving the traffic flow (Target 11.7) (Karthik et al. 2023). Local communities in smart sustainable cities should be engaged and empowered to participate in these waste management activities. This step should be supported by acquiring sufficient information on the city corporations' and municipalities' average annual waste production.

1.6.12 SDG12: Responsible Consumption and Production

The manufacturing of domestic materials (e.g., food, shelter, clothing) is increasing exponentially to satisfy the economic requirements because all human wants to have some basic common characteristics. Some solid wastes can be used as a resource needed for the creation of a good or service, further achieving economic growth (Target 12.4). The quantities and types of solid wastes recycled to recover valuable items (e.g., computers, chemicals, nutrients, furniture, phones, and bags) vary according to industrialization and elevated population expansion (Target 12.5) (Mohod and Bagal 2023). Renewable natural resources (air, solar, plant, soil, and water) should be utilized efficiently (Target 12.2), and a large amount of generated waste should be reused and recycled to avoid inadequate sequential production/consumption schemes (Aboughaly and Fattah 2023). This approach attempts to eliminate the barriers in order to transform the linear economy into the circular economy (Subbarao et al. 2023), needing awareness and education programs (Target 12.1).

1.6.13 SDG13: Climate Change

The world is facing climate crises and catastrophes, including sea levels rising, Arctic ice melting, coral reefs dying, ocean acidification, and forest burning. Proper SWM can mitigate the increase in the anthropogenic emissions caused by various human activities (Target 13.1), e.g., domestic and industrial waste dumping, fossil fuel combustion, transportation, and unplanned landfilling (Themelis 2023). Waste transformation reduces CH_4 emissions from cattle digestion (enteric emissions) and stored manure, and CO_2 released road transport, and offshore drilling, contributing to climate change (Syarifinnur et al. 2023). The implementation of AD to treat biogenic organic wastes addresses the targets of SDG13 by capturing CH_4, which is then used beneficially. Raising awareness of climate change and health (Target 13.3) supports developing countries in securing grant funding and access to key experts under the United Nations Framework Convention on Climate Change (UNFCCC) framework (Zhang et al. 2023). This framework promotes effective climate change-related plans and mechanisms to avoid human influence on the climate system (Target 13.b) (Shea and Thornton 2019).

1.6.14 SDG14: Life Below Water

Several strategies are proposed to avoid the dumping of solid wastes into aquatic ecosystems, which are used to protect the quality of oceans and seas (the planet's largest ecosystem) (Target 14.2) (Zidan et al. 2023). This approach is highly linked to marine species' growth and health and maritime transport services (boat, ship, sailboat, or barge) (Dadebo et al. 2023b). Moreover, it avoids the escape of various fish types and many planktonic organisms (Target 14.1), making the seafood supply chain more sustainable (Midden et al. 2023).

1.6.15 SDG15: Life on Land

Pollution (e.g., leachate pollution) can transfer from solid wastes to terrestrial ecosystems, causing significant environmental problems especially if the waste contains toxic substances. For instance, deforestation and desertification caused by human activities and climate change deteriorate biological diversity and healthy ecosystems. An efficient stabilization of this waste before reaching the soil matrix, obtaining less soluble, mobile, or toxic forms of waste, is of significant importance (Target 15.1) (Mohod and Bagal 2023). Reducing the amount of waste from the source is required to maintain sustainable management of land for agriculture and tourism (Podder et al. 2589). Education program on ecosystems is essential to avoid biodiversity loss (Target 15.9).

1.6.16 SDG16: Peace, Justice and Strong Institutions

Waste management projects aim at providing advanced solutions to waste and pollution, supporting a global shift toward environmental justice (Target 16.3). The purpose of institutions, along with their function and philosophy, is to allow the organizational requirements to initiate and establish waste management projects. SDG 16 ensures that other goals act synergistically together to reduce all causes of environmental depletion, such as the accumulation of solid wastes in streets, landscapes, and urban areas (Target 16.7). The four primary sociological institutions, e.g., family, religion, education, and government, should be involved in maintaining a healthy environment through the recovery of green material and renewable and clean energy from solid waste recycling (Target 16.8). As such, proper environmental management and governance are important for long-term peace, stability, and security in disaster-prone countries, mainly, in communities that depend on natural resources for their survival (Chiaramonti and Panoutsou 2018).

1.6.17 SDG17: Partnership for Goals

Several developing countries are facing considerable challenges in achieving the "waste-to-energy" strategy. These barriers include (i) operational challenges (e.g., site selection, and waste segregation, collection, and transportation), (ii) technical challenges (e.g., advanced and modern technologies of recycling, personnel's knowledge and awareness, lower calorific value for high-moisture wastes, and atmospheric damage), (iii) economic challenges (e.g., project budget, installation, and maintenance), and (iv) managerial challenges (e.g., training and continual support, and communication gap between researchers and the government, collaboration from stakeholders) (Shea and Thornton 2019). International collaboration between developed and developing countries should include technical assistance and capacity building to strengthen the solid waste recycling approach.

1.7 Suggestions for Maintaining Efficient Utilization of Solid Wastes

- The waste management systems and infrastructure should be upgraded to receive the large amounts of solid waste.
- Organic wastes should not be contaminated with potentially toxic bio-contaminants, e.g., antibiotics and heavy metals, before entering the digesters.
- This biogas can be used in electric power generation, reducing the dependence on fossil fuels (e.g., coal, petroleum, natural gas) (Themelis 2023).