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Uporedna analiza regionalnog upravljanja čvrstim komunalnim otpadom, tehnologije upravljanja i njihova primena

Konstantina Mitsigiorgi[1], Aikaterina L. Stefi[2], Konstantinos E. Vorgias[3*]

[1]Section of Botany, Department of Biology, National and Kapodistrian University of Athens, Panepistimiopolis Zografou, 15784 Athens, Greece, mitsig@biol.uoa.gr
[2]Section of Botany, Department of Biology, National and Kapodistrian University of Athens, Panepistimiopolis Zografou, 15784 Athens, Greece, kstefi@biol.uoa.gr
[3]Section of Biochemistry and Molecular Biology, Department of Biology, National and Kapodistrian University of Athens, Panepistimiopolis Zografou, 15784 Athens, Greece, cvorgias@biol.uoa.gr

Apstrakt: Kako se globalno stvaranje otpada nastavlja povećavati, neophodno je ispitati kako se sastav čvrstog komunalnog otpada razlikuje u različitim kulturnim i ekonomskim kontekstima. Ova varijacija utiče i na prakse upravljanja otpadom i na strategije ublažavanja klimatskih promena. Različiti kulturni konteksti dovode do prepoznatljivih obrazaca otpada, koji su oblikovani načinom života, obrascima potrošnje i lokalnim ekonomskim uslovima. Ova raznolikost naglašava potrebu za prilagođenim pristupima tretmanu otpada. Zemlje u razvoju mogu naići na prepreke u usvajanju naprednih tehnologija upravljanja otpadom zbog finansijskih ograničenja, dok razvijeni regioni mogu primeniti sofisticirane tehnologije kao što su hvatanje deponijskog gasa, anaerobna digestija i sistemi za pretvaranje otpada u energiju. Rad naglašava najsavremenije tehnologije koje nude obećavajuća rešenja za smanjenje emisija. Adaptacija i implementacija ovih tehnologija zavise od regionalnih i kulturnih varijacija, uključujući dostupnost lokalnih resursa i infrastrukture. Istaknuta je interakcija između praksi upravljanja otpadom i klimatskih promena, naglašavajući važnost kontekstualno specifičnih, isplativih rešenja u negovanju održivih sistema upravljanja otpadom koji doprinose globalnim ciljevima ublažavanja klimatskih promena. Razvoj i primena ovih tehnologija u velikim razmerama biće ključni u rešavanju rastućih izazova upravljanja otpadom i klimatskih promena.

Ključne reči: čvrsti komunalni otpad, gradski otpad, ublažavanje klimatskih promena, upravljanje otpadom, tehnologije, regionalno poređenje

A Regional Comparison of Municipal Solid Waste Management, Technologies and their Implementation

Abstract: As global waste generation continues to increase, it is imperative to examine how municipal solid waste composition varies across diverse cultural and economic contexts. This variation impacts both waste management practices and climate change mitigation strategies. Diverse cultural contexts give rise to distinctive waste patterns, which are shaped by lifestyle, consumption patterns, and local economic conditions. This diversity underscores the necessity for customized approaches to waste treatment. Developing countries may encounter obstacles in adopting advanced waste management technologies due to financial constraints, while developed regions may implement sophisticated technologies such as landfill gas capture, anaerobic digestion, and waste-to-energy systems. The paper emphasizes cutting-edge technologies which offer promising solutions for reducing emissions. The adaptation and implementation of these technologies are contingent on regional and cultural variations, including the availability of local resources and infrastructure. The interplay between waste management practices and climate change is highlighted, underscoring the importance of context- specific, cost-effective solutions in fostering sustainable waste management systems that contribute to global climate mitigation goals. The development and large-scale implementation of these technologies will be crucial in addressing the growing challenges of waste management and climate change.

Keywords: Municipal Solid Waste, Urban Waste, Climate Change Mitigation, Waste Management, Technologies, Regional Comparison

1. Introduction

The rapid growth of urbanization, industrialization, and consumerism has led to an unprecedented increase in municipal solid waste (MSW) worldwide. MSW refers to waste generated by households, commercial establishments, institutions, and other non-industrial sources within a municipality. Its composition varies significantly depending on population density, socioeconomic status, cultural practices, and waste management infrastructure. Global MSW generation is predicted to grow from 2.1 billion tonnes in 2023 to 3.8 billion tonnes by 2050. Despite efforts to enhance waste management, only 13% of waste is converted into energy, 19% is recycled, and 68% still ends up in landfills or is openly dumped—leading to severe environmental, economic, and public health consequences (U.N.E.P., 2024). The environmental impact of MSW is significant, particularly due to greenhouse gas (GHG) emissions from landfills and incineration, which contribute directly to climate change (Wang et al., 2017). Landfilling, the most common waste disposal method, releases methane (CH_4) through organic waste decomposition, a greenhouse gas 25 times more potent than CO_2. Open dumping and incineration—widely practiced in low- and middle-income countries—contribute to carbon monoxide (CO), black carbon (soot), and particulate matter emissions, worsening air pollution and accelerating climate change (U.N.E.P. and C.C.A.C., 2021). To address these challenges, researchers and industries are exploring waste valorisation—the process of converting MSW into biofuels, chemicals, and raw materials—as a sustainable alternative to conventional disposal (Kaza et al., 2018). However, valorisation remains economically and technologically challenging due to high capital costs, operational inefficiencies, and the heterogeneous nature of MSW, which varies regionally and seasonally (Velvizhi et al., 2022; Velenturf et al., 2019). A crucial yet often overlooked factor in waste management is cultural influence. Waste composition and disposal methods differ across regions due to economic conditions, consumption habits, recycling infrastructure, and regulatory frameworks. Understanding these cultural and socioeconomic variations is essential to designing effective, climate- resilient waste management strategies. This review examines:

- The impacts of MSW across different cultural and economic contexts.
- Cutting-edge technologies aimed at optimizing MSW management.

2. Impacts of Municipal Solid Waste Across Different Cultures

2.1. Waste Composition and Cultural Variations

The composition of MSW is highly diverse, influenced by geography, economic development, seasonal variations, and cultural behaviors. Waste generation has a positive correlation to Gross Domestic Product (GDP), as high-income countries generate more waste per capita and in total (Kaza et al., 2018). The primary components of MSW include organic waste (food and yard waste), paper and cardboard, plastics, glass, metals, rubber and wood. Waste composition also fluctuates in relation to income. High-income countries generate large amounts of plastic packaging, electronics, and processed food waste due to higher consumption levels and food transport needs. Their waste management systems emphasize on recycling, incineration with energy recovery, and landfill gas capture. Middle- income countries face increasing waste challenges, with rising industrial and urban waste generation. They often lack advanced recycling or waste-to-energy (WtE) infrastructure, leading to higher rates of open dumping and informal waste collection. Low-income countries generate a relatively greater proportion of organic waste (food and agricultural residues), due to the limited amount of packaging used. but have limited access to waste treatment facilities. In many cases, open burning and uncontrolled landfilling are common, exacerbating GHG emissions and public health risks (U.N.E.P., 2024). In terms of management, MSW is composed of 40% biowaste, 40% recyclable content, 10% bulky waste and 10% other types. The organic fraction of MSW (agro and food waste) consists of approximately 30-69% carbohydrates (starch, cellulose and hemicelluloses), 5-10% proteins and 10- 40% lipids and has great potential to produce fuels and value-added products. Its exact composition varies depending on the geographical location and season (Zabaleta et al., 2017). On a global scale, waste generation per capita averages 0.74 kg per day, ranging from 0.11 kg in low-income regions to
4.54 kg in high-income nations (Karak et al., 2012). Though they make up only 16% of the world‘s population, high-income nations account for 34% (683 million tons) of total waste. By 2050, low- income countries are projected to generate three times their current waste levels, increasing their environmental burden (Kaza et al., 2018). The geographical distribution of waste generation also plays a role in emissions. The East Asia and Pacific region generate the largest amount of waste, while the Middle East and North Africa produce the least (Kaza et al., 2018).

Rapid waste growth in Sub-Saharan Africa, South Asia, and the Middle East is accelerating environmental risks due to poor infrastructure and limited policy enforcement. Understanding these cultural and regional differences in waste composition is crucial for designing targeted mitigation strategies that address both waste reduction and climate resilience.

2.2. Waste Management Practices

The management strategies employed by MSW adhere to the principles of the waste management hierarchy, a system that prioritizes upstream measures for the prevention of waste. The fundamental objective of this hierarchy is to minimize waste generation, with a focus on the repair and reuse of goods whenever feasible. Downstream measures to mitigate the impacts of waste on the environment include recycling, energy/resource recovery and disposal. Sustainable waste management practices aim to minimise waste generation, maximise resource recovery, and promote circular economy principles to reduce reliance on landfilling and incineration. According to the United Nations‘ Environment Programme Global Waste Management Outlook (2024), until 2020 38% of MSW generated globally was dumped or burned uncontrollably. In low-income regions where formal waste collection is lacking, open burning of waste is a widespread practice. This process releases black carbon, dioxins, and other air pollutants, contributing to climate change and respiratory illnesses. The remaining 62% of waste is managed controllably, with 30% of the MSW disposed of in landfills, while 13% was converted to energy and 19% was recycled. Landfills remain the dominant waste disposal method worldwide. In many developing regions, landfills lack methane capture systems, allowing large quantities of CH_4 to escape. Their significant contribution to GHG emissions, makes landfills a major driver of climate change (Kaza et al., 2018). Recycling rates vary significantly by region, influenced by government policies, economic incentives, and cultural attitudes toward waste. In high-income nations, formalized recycling programs process materials such as plastics, paper, and metals. In contrast, informal waste- picking economies play a crucial role in waste recovery in middle- and low-income countries, often without government support or regulation. Worldwide, researchers are conducting extensive studies to convert MSW into fuel and valuable chemicals using thermal and biochemical processes (Awasthi et al., 2022). To tackle the technological and economic challenges, the scientific and industrial communities have made significant efforts to develop novel, innovative, and cost-efficient waste valorisation processes that are more sustainable (Kumar et al., 2023).

2.3. Differences in Waste Management Between Countries

Africa

Municipal waste management in Africa faces significant challenges due to rapid urbanization, population growth, limited infrastructure, and financial constraints. Many African cities struggle with inadequate waste collection services, leading to widespread illegal dumping, open burning, and poorly managed landfills, practices that pose a significant environmental threat and loss of resources (Scarlat et al., 2015). More than 80% of MSW is deposited in a landfill or uncollected, while 5% is recycled and less than 1% is used for energy recovery (U.N.E.P., 2024). The uncollected waste ends up in waterways and informal dumpsites, contributing to severe environmental and public health issues. Formal recycling systems and legislation remain underdeveloped, and waste management largely relies on the informal sector, where waste pickers recover valuable materials such as plastics, metals, and paper for resale (Thabit et al., 2023). Despite these challenges, several African nations have made strides toward improving waste management practices. Countries like South Africa, Rwanda, and Ghana have introduced national policies promoting waste reduction, recycling, and sustainable disposal methods. Rwanda has implemented one of the world‘s strictest bans on plastic bags, significantly reducing plastic pollution (Behuria, 2021). South Africa has developed an extended producer responsibility (EPR) framework to encourage industries to take responsibility for the entire lifecycle of their products, including post-consumer waste recovery (Laubinger &Börkey, 2023). Innovative waste management solutions are emerging throughout the continent. These initiatives include community-led recycling programs, biodegradable packaging, and digital waste tracking systems.

North America

North America‘s MSW management is characterized by a diverse range of strategies, influenced by regional policies, economic factors, and technological advancements. The United States and Canada generate significant amounts of municipal solid waste (MSW), with 2 kilograms of waste production per capita per day, amongst the highest globally (U.N.E.P., 2024).

The majority of MSW consists of packaging material, and organic waste takes up 30% of the composition, one of the lowest percentages globally. While both countries have made progress in recycling and waste-to-energy (WTE) initiatives, landfilling remains the dominant waste disposal method, particularly in the United States, where over 50% of MSW is still sent to landfills. Out of 292 million tons of MSW generated in 2018, more than 146 million were landfilled, while 69 million were recycled, 25 million were composted and 34 million were combusted with energy recovery. In addition, about 18 million tons of food were processed through other food management pathways (U.S. E.P.A., 2020). In contrast, Canada has implemented more extensive waste diversion programs, with higher recycling and composting rates in certain provinces. Recycling infrastructure and policies vary significantly across states, provinces, and municipalities, leading to inconsistencies in waste management effectiveness. Cities such as San Francisco have implemented ambitious zero-waste strategies, emphasizing source separation, food recovery, extended producer responsibility (EPR), and bans on single-use plastics. (City and County of San Francisco, 2022). However, other regions continue to struggle with contamination in recycling streams and limited markets for recycled materials. Waste- to-energy technologies are gaining traction in North America, with 60 waste-to-energy plants operating in the United States in 2022, with a total generating capacity of 2,051 megawatts. These facilities reduce landfill dependency and generate electricity. In 2022, over 12.000 gigawatthours were generated from the combustion of municipal biogenic and non-biogenic solid waste (U.S. E.I.A., 2023). Organic waste diversion is also expanding, with composting and anaerobic digestion programs being promoted to reduce methane emissions from landfills. Emerging technologies, such as artificial intelligence for waste sorting, chemical recycling, and blockchain-based waste tracking, are gradually improving waste management efficiency.

South America

Municipal waste management in South America presents a diverse landscape, with significant variations in waste handling practices across countries and cities. A distinctive characteristic of MSW in South America is its high organic content, which is typical of many developing regions. This composition presents both a challenge and an opportunity: while organic waste contributes to environmental pollution when mismanaged, it also holds potential for composting and biogas production if properly treated. Rapid urbanization, economic disparities, and insufficient infrastructure pose major challenges, leading to high levels of landfill dependency and informal waste collection (Hettiarachchi et al., 2018). Many Latin American countries still rely on open dumps, which contribute to environmental degradation, air and water pollution, and greenhouse gas emissions. However, growing awareness of sustainability and climate change has prompted governments and municipalities to implement new policies aimed at improving waste management efficiency and promoting circular economy principles. Governance deficiencies remain a critical barrier, as the MSW system is complex and involves multiple stakeholders. Strong regulatory frameworks and institutional coordination are required to ensure effective waste collection and processing. Weak governance structures have led to environmental and health problems due to improperly managed waste (Hettiarachchi et al., 2018). Recycling rates in South America remain relatively low, while the informal sector plays a crucial role in waste recovery, with waste pickers collecting and sorting recyclable materials (Ferronato et al., 2018). Innovative waste management initiatives are emerging in cities like Bogotá, São Paulo, and Mexico City, where local governments are investing in waste-to-energy (WTE) facilities, composting programs, and digital platforms to optimize waste collection. Some countries have also introduced zero-waste policies to minimise landfill use and promote sustainable waste management.

Asia

Municipal waste management in Asia presents a complex and highly varied landscape, influenced by rapid urbanization, population growth, and economic disparities. East and South-East Asia is the highest producer of MSW in the world, with a production of over 550 million tonnes of MSW in 2020, the majority of which is uncontrolled (U.N.E.P., 2024). Many Asian countries face significant challenges in handling increasing volumes of MSW, with waste collection and disposal infrastructure struggling to keep pace. China is currently the largest emitter of CH_4 in the world, accounting for 15.7% of global emissions in 2022 (I.E.A., 2024). However, between 2019 and 2021, China launched a zero-waste pilot program in 11 cities to promote sustainable urban development, circular economy practices, and emissions reductions, which was later expanded to 100 cities under the 14th Five-Year Plan due to its success. These ‗zero-waste cities‘ aim to minimise solid waste through green lifestyles, industry practices, and eco-park developments, with strong emphasis on public engagement and social media-driven participation (U.N.E.P., 2024).

Japan‘s advanced waste management system relies heavily on incineration with energy recovery, strict waste segregation, and strong public participation, all supported by comprehensive legal and educational frameworks promoting the 3Rs (Reduce, Reuse, Recycle) (Vuk et al., 2025). South Korea‘s waste management system is built on strict segregation, high recycling rates, volume-based fees, and strong public engagement, supported by policies like extended producer responsibility and digital monitoring tools (Vuk et al., 2025). Despite progress, many developing Asian nations continue to struggle with inadequate waste collection, illegal dumping, and plastic pollution.
India‘s MSW management faces major challenges due to a significant lack of data from rural areas, making it difficult to accurately assess waste generation and plan infrastructure. As a result, open waste burning remains a widespread disposal method, posing serious environmental and health risks (Chaudhary et al., 2021). The informal recycling sector plays a critical role in waste recovery across much of Asia, with waste pickers and small-scale recyclers handling a significant portion of material sorting and processing, often in hazardous conditions.

Australia

Australia's approach to municipal waste management is undergoing a transformative phase, driven by a confluence of factors including stringent national policies, advancements in waste treatment technologies, and a heightened public consciousness regarding environmental stewardship. Although as much as 50% of MSW is recycled in Australia, over 40% is still being directed to landfill sites, while less than 5% is being converted into energy (U.N.E.P., 2024). As a nation with one of the highest per capita waste generation rates on a global scale along with North America, Australia faces persistent challenges in its efforts to limit its reliance on landfill disposal. The National Waste Policy Action Plan, launched in 2019, epitomises the country's commitment to transitioning towards a circular economy model, characterised by ambitious objectives such as the phasing out of problematic plastics, enhancing resource recovery rates, and promoting the incorporation of recycled materials into manufacturing processes (D.C.C.E.E.W. 2024). Extended producer responsibility schemes have been implemented across diverse sectors, including electronics, packaging, and battery production, thereby ensuring that manufacturers assume responsibility for the post-consumer lifecycle management of their products. Waste-to-energy technologies, encompassing incineration and anaerobic digestion, are being actively explored as viable alternatives, with pilot studies being explored (Esfilar et al., 2021) and new waste-to-energy facilities are currently under development (Australian Renewable Energy Agency, 2024). Simultaneously, organic waste diversion initiatives are proliferating across the country, with local councils implementing green waste collection programs and composting facilities to mitigate methane emissions from landfills. These initiatives are crucial for reducing the environmental footprint of waste management and promoting the recovery of valuable resources from organic waste streams (Blanchard et al., 2023). A high percentage of MSW is recycled, as the Australian government has invested in local recycling infrastructure, including material recovery facilities and advanced sorting technologies, to improve the quality of recyclable materials and reduce reliance on overseas processing. Additionally, consumer-focused initiatives, such as plastic bags,deposit refund schemes for beverage containers, and public education campaigns, are helping to drive behavioral change (D.C.C.E.E.W. 2024).

Europe

Europe has established itself as a global leader in municipal waste management through stringent policies, innovative technologies, and a commitment to sustainability. The European Union (EU) has set ambitious waste reduction targets under the Circular Economy Action Plan, which mandates recycling, waste prevention, and sustainable product design (European Commission, 2020). In northern and western European countries 44% and 56% of MSW is recycled respectively, and another 42% and 34% respectively is transformed into energy. Southern and Eastern European countries still have a high percentage of landfilling at 40 and 45% as of 2020, but with potential to rapidly reduce it through the implementation of Directive 2018/851 (EU‘s Landfill Directive). This Directive introduces restrictions on landfilling of all waste that is suitable for recycling or other material or energy recovery from 2030 and sets a goal of 60% recycling of each EU country‘s MSW by weight, by 2030 (European Parliament & Council of the European Union, 2018). Germany, Austria, Slovenia, the Netherlands, Belgium, Luxembourg, Italy, and Denmark are the top eight EU countries in MSW recycling and composting, while Sweden, Finland, Denmark, Belgium, Estonia, the Netherlands, and Luxembourg are the top seven EU countries in terms of waste-to-energy and incineration rates of their own generated municipal waste. Malta, Greece, Romania, Cyprus, Bulgaria, Croatia, Hungary, Latvia, Spain, Portugal, and Slovakia are the top EU countries that use landfilling for the majority of their MSW (Eurostat, 2020).

Composting and anaerobic digestion have also gained prominence, while digital innovations, such as AI-driven waste sorting and blockchain-based tracking systems, are enhancing recycling efficiency and waste transparency across the region.

3. Cutting-Edge Technologies for MSW Management in Diverse Waste Contexts

3.1. Landfill Gas Capture and Utilisation

Landfill gas (LFG) consists mainly of methane (50-55%) and carbon dioxide (45-50%), along with water vapor, hydrogen sulphide and other compounds in smaller concentrations, and derives from the decomposition of the organic fraction of municipal waste (Lam &Lashaki, 2025). It is typically collected through a network of pipes and can be used as a gas after moisture removal (primary treatment) and hydrogen sulphide separation (secondary treatment). It can be further treated to remove impurities (advanced treatment) with a consistency of 96-98% biomethane, also known as renewable natural gas (RNG). RNG can be used by vehicles or through the gas pipeline system for heating. Cutting edge technologies focus on the simultaneous removal of several impurities, to simplify the treatment procedure. Table 1 presents the latest scientific advancements related to landfill gas purification and utilisation.

Table 1: Cutting-edge technologies for landfill gas utilisation.

Technology	Result	Reference
TRI-tethered G-10 silicas	Full performance throughout successive adsorption-desorption cycles, successful capture of H_2O, CO_2 and H_2S in one single step to produce RNG.	Lam &Lashaki, 2025
ECCS-CCU process based on CO_2 mineralization with NaCl	Generates biomethane and valuable chemicals (Na2CO3, Cl2, pure dense CO2 and Green-H2) while consuming water, NaCl,electricity and LFG.	Rodrigues et al., 2024
Steam Methane Reforming of LFG to Green H_2	Comparison of the economic and environmental aspects of Steam Methane Reforming, Dry Methane Reforming, Partial Oxidation Reforming, Autothermal Reforming.	Singh et al., 2025
chemical looping reforming of LFG with LaFe1-xNixO$_3$ perovskite oxygen carrier	Combined syngas and hydrogen production.	Yao et al., 2025
Ultra-rich combustion mode via porous reactor	Efficient H2-rich syngas production from low-calorific value LFG.	Mohammadpour et al., 2025

However, many developing countries have not incorporated landfill gas collection technologies yet, and the cost of the infrastructure needed can be substantial. Therefore, in order to mitigate the effects of landfill gas and especially methane, low - cost technologies that are easy to implement should also be examined. Verma et al. (2025a) propose a Biogeochemical Cover System (BGCC) for landfill gas mitigation—specifically targeting methane (CH_4), carbon dioxide (CO_2), and hydrogen sulfide (H_2S) emissions from municipal solid waste landfills. BGCC consists of layers of biochar-enhanced soil (for methane oxidation) with Basic Oxygen Furnace (BOF) steel slag for CO_2 and H_2S capture. The BGCC system has strong potential for application in developing countries, especially if biochar can be produced from local agricultural residues, such as rice husk, almond shell, walnut shell, corn stalk and hemp stalk (Verma et al., 2025b) and BOF slag or equivalent alkaline materials such as limeare locally available.

3.2. Anaerobic Digestion & Bioenergy Production

Anaerobic digestion technologies convert the organic fraction of MSW into methane and can be used in a wide spectrum of applications, from small scale individual systems to large, industrial scale plants. In the Sichuan Province of China, small-scale biogas plants are provided to low-income rural households, to support rural development and environmental protection. The biogas plants digest manure and recover the methane and digestate by-product through the process of anaerobic digestion, offering clean and affordable energy to homes and fertilizer for agriculture.

In addition to reducing greenhouse gas (GHG) emissions, the project improves indoor air quality and sanitation for rural communities (C.S.E.S., 2017). Rubber-balloon biogas plants or fixed-dome plants are also affordable and simple to construct and operate (I.S.A.T. & G.T.Z., 1999). Large scale plants are established in Europe and China, while associations such as the European Biogas Association (EBA) are committed to the deployment of sustainable biogas and biomethane production and use. China produces 8,500 Mm³/year of biogas through industrial scale plants, with an electricity capacity of 1,747 MW (Gustafsson et al., 2024). Germany has the highest number of biogas plants in Europe with over 10,000 industry scale plants, producing around 87 TWh/y, that is the highest global annual biogas production (Gustafsson et al., 2024). Recent advancements in anaerobic digestion technologies are analyzed by Uddin & Wright (2023). In principle, all biodegradable organic materials can undergo anaerobic digestion to generate biogas. However, the feedstock should be easily degradable and free from toxic substances that could harm the bacteria involved in the process. To enhance the hydrolysis or solubility of organic matter, various pretreatment methods—thermal, chemical, or mechanical—can be applied. Additionally, there is growing interest in recovering intermediate products like volatile fatty acids (VFA).

3.3. Carbon Capture in Waste Incineration

Waste thermal processing is a favorable alternative to landfilling, as it frees the area required for landfills, while limiting the methane emissions and producing energy as a byproduct of waste management, effectively lowering the treatment cost. Thermal processing methods include incineration, torrefaction, gasification, pyrolysis, conversion to refuse-derived fuel and plasma arc gasification. Waste incineration is used the most, as it is efficient and can be easily applied in relation to other thermal processing methods. However, the combustion process produces CO2 emissions that contribute to climate change. These emissions can be significantly reduced with the application of Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) technologies (CCUS). Integrating CCUS technologies to WtE incineration plants is complex, as it involves technical, regulatory, and economic considerations (Bertone et al., 2024). CCS is a technology aimed at storing CO2 permanently after capturing it. while CCU integrates it into the carbon cycle and reuses it to generate economic benefits (Tan et al., 2016; I.E.A., 2019). Most of the technologies associated with CCUS carry a significant investment cost that developing countries might not be able to cover. Solutions involve the pursuit of international funding and partnerships, as well as the retrofitting of existing coal powered power plants, and the construction of small-scale projects. Biochar production is also an alternative way of CCU that provides carbon sequestration and a method of improving soil health. In terms of cutting-edge technologies for more effective CCU pathways, El Helou et al. (2025) propose the incorporation of hydrogen injection into the CO2 removal separators. This process allows for a 48 %-77 % reduction in the net energy consumption for flue gas and syngas respectively. Biogenic CCU from flue gas of paper and steel industries can be utilised for the sustainable co- production of a high-value chemical component of liquid detergents (alcohol ethoxylate - AE7) and low-medium distillate range liquid fuel (Sadhukhan et al., 2025). Rodriguez et al. (2025) present a novel multienzymatic CCU platform that simultaneously converts industrial CO_2 emissions and crude glycerol waste into formate and dihydroxyacetone under mild, eco-friendly conditions, enabling efficient cofactor regeneration and green product recovery. An integrated carbon capture and utilisation (ICCU) approach combined with dry reforming of methane (DRM) is proposed by Li et al., (2025), demonstrating superior energy efficiency, economic viability, and CO_2 mitigation potential—especially when driven by solar energy—compared to conventional CCU systems. Regarding CCS, a high- resolution dynamic optimization model (PSOM) can be used to integrate three types of retrofitted CCS technologies (dedicated coal-fired coupled with CCS technology, dedicated gas-fired coupled with CCS technology, and coal-biomass co-firing coupled with CCS technology) into a national power system while accounting for hourly provincial-level variations in renewable energy availability and demand—enabling a detailed, scalable assessment of retrofitted CCS‘s role in cost-effective decarbonization (Zhou et al., 2025). Sun et al. (2025) offer that biomass and coal co-firing with carbon capture and storage (BCP-CCS) can help China reach its carbon neutrality goals by retrofitting existing coal-fired power plants rather than phasing them out entirely, by proposing a plant-level, high-resolution ‗ternary-matching‘ strategy that couples biomass residues, coal-fired power plants, and nearby carbon sequestration sites to realistically assess the retrofit potential, cost, and carbon reduction of BCP-CCS, addressing resource competition and geographic constraints. The CCS innovation dynamics in Norway were analyzed with the application of the Technological Innovation System (TIS) framework, focusing on the structural and functional aspects of the system and its weaknesses.

While there are positive developments, such as increasing R&D activity and demonstration projects, the Norwegian CCS innovation system faces systemic challenges, particularly in market formation and resource mobilization, with current political and financial frameworks insufficient to drive large-scale investment (Steen et al., 2024). Laljee&AlHajaj (2025) introduce an optimization-based model for designing cost-optimal CO2 pipelines that account for impurities, revealing that impurities significantly increase compression energy and transport costs, with a proposed penalty scheme to mitigate these costs, highlighting the need for impurity control in efficient CCS deployment.

4. Conclusions

The growing challenge of managing municipal solid waste (MSW) is a multifaceted issue that requires a comprehensive understanding of regional differences, cultural practices, and technological limitations. As urbanization accelerates on a global scale, nations encounter a variety of waste management challenges, ranging from inadequate infrastructure and high landfilling rates in low- income regions to advanced recycling and waste-to-energy systems in high-income nations. The development of effective waste management strategies must address these disparities and promote sustainable practices through a circular economy model, resource recovery, and waste minimization efforts. The integration of innovative technologies, the enhancement of policy frameworks, and the promotion of public engagement present a substantial opportunity to mitigate the environmental, economic, and health ramifications of MSW. A concerted, worldwide effort to adopt more sustainable waste management practices will necessitate collaboration between governments, industries, and local communities to devise customized solutions that curtail waste generation, enhance recycling rates, and curtail reliance on landfills and incineration. Such efforts must be pursued in a manner that fosters climate resilience and environmental sustainability. The advancements in MSW management that are being developed and implemented at present demonstrate the potential for significant environmental, economic, and societal benefits. Technologies such as landfill gas capture and utilization, anaerobic digestion, and carbon capture in waste incineration represent critical components of sustainable waste management systems. The potential for converting landfill gas into renewable natural gas (RNG) represents a significant opportunity to curtail methane emissions while generating a valuable energy source. Similarly, anaerobic digestion technologies offer a dual benefit of generating bioenergy while reducing the environmental impact of organic waste. Furthermore, the integration of carbon capture, utilization, and storage (CCUS) in waste-to-energy (WtE) processes can significantly mitigate carbon dioxide (CO2) emissions, thereby contributing to climate change mitigation efforts. However, these technologies face significant challenges, including high infrastructure costs and limited technological accessibility in developing countries, which act as substantial barriers to their full implementation. However, the development of cost-effective, scalable solutions, such as the Biogeochemical Cover System for landfill gas mitigation, offers a potential solution for addressing these challenges in developing regions. As research progresses and new technologies continue to emerge, the evolution of MSW management towards more sustainable, circular economy models will be crucial in addressing global environmental concerns while fostering economic development, particularly in underserved communities.

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