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Review

Assessment of Solid Waste Management and Decarbonization Strategies

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Abstract: Global population growth, industrialization, and urbanization have led to a dramatic increase in solid waste (SW) generation, which is considered a main environmental pollutant via greenhouse gas (GHG) emissions and soil and groundwater contamination. This creates serious problems for the region and the world at large. Currently, about 2 billion tons of SW are generated globally every year, of which 67% is processed by various treatment technologies, while 33% is freely released into the environment. Therefore, there is an urgent need to significantly reduce GHG emissions from global SW production for the maximization of climate benefits and to halt the continued rise in temperature. Fortunately, this can be attained with the use of existing SW processing methods and improved performance. Through a comprehensive literature review, this research evaluates the effectiveness of various SW approaches, including source reduction, recycling, and energy recovery. Additionally, this study examines the potential of emerging technologies and their integration and innovative solutions to enhance solid waste management (SWM) systems and promote decarbonization. The findings highlight the significant environmental and economic benefits of implementing integrated SWM strategies that prioritize waste prevention, material recovery, and energy generation from waste. Furthermore, this study emphasizes the importance of stakeholder engagement, policy interventions, and public awareness campaigns in fostering sustainable waste management practices. By adopting a holistic approach that considers the entire waste management lifecycle, this review provides valuable insights and recommendations for policymakers, waste management authorities, and communities to achieve sustainable waste management and contribute to global decarbonization efforts.

Keywords: solid waste management; economic policy; climate change; mitigation technologies; carbon recycling

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1. Introduction

Population growth has led to an increasing amount of solid waste (SW), and the total annual global SW production is expected to reach 3.4 billion tons by 2050 [1]. This will bring about various ecological challenges, including climate change, due to improper handling of the total waste generated annually, as 33% of the 2 billion tons of waste generated is not treated. Moreover, climate change encompasses changes in the Earth's

climate at a variety of spatial scales, such as regional, continental, hemispheric, and global; and historical time scales, such as decadal, secular, millennial, and multimillennial. These changes are manifested in one or more environmental and climatic parameters, in particular, the average values of temperature (including mean, maximum and minimum values), precipitation, cloud cover, ocean temperature, and the distribution and development of flora and fauna [2]. Solid waste management (SWM) and decarbonization are two critical components of sustainable development that are intrinsically linked. As the global population continues to grow and urbanization accelerates, the generation of SW escalates, posing significant challenges for waste management systems worldwide. Concurrently, the urgent need to mitigate climate change has brought decarbonization efforts to the forefront of environmental policies and strategies. The intersection of SWM and decarbonization offers a pathway to address these interconnected challenges. Improper waste management practices not only contribute to environmental degradation and public health risks, but also exacerbate greenhouse gas (GHG) emissions, which are a primary driver of climate change. Conversely, effective SWM strategies can play a pivotal role in reducing GHG emissions and promoting a transition towards a low-carbon economy [3].

Traditionally, SWM has focused on public health and environmental protection, with the primary objectives of collecting, treating, and disposing of waste in a safe and efficient manner. However, the growing recognition of the climate change crisis has necessitated a paradigm shift, where SWM must be integrated with broader decarbonization strategies to minimize the carbon footprint of such waste management activities. The urgency of this integration is underscored by the staggering volumes of SW generated globally. The World Bank estimates that waste generation is projected to rise from 1.3 billion tons in 2012 to 2.2 billion tons by 2025 and further to 3.4 billion tons annually by 2050, signifying a substantial 70% increase in waste production [4]. This surge in waste production, coupled with the continued reliance on landfilling and incineration as primary disposal methods, poses a significant threat to the environment and exacerbates climate change through the release of methane (CH_4) and other GHGs. Addressing this challenge requires a comprehensive approach that encompasses waste reduction, recycling, energy recovery, and the adoption of sustainable waste management practices aligned with decarbonization goals. By diverting waste from landfills and incinerators, and by harnessing the potential of waste-to-energy technologies, SWM can contribute to reducing GHG emissions while simultaneously generating renewable energy [5]. Moreover, the integration of SWM and decarbonization strategies has the potential to drive innovation and technological advancements in areas such as waste processing, recycling, and energy recovery. This, in turn, can create economic opportunities and foster the development of a circular economy, where waste is viewed as a valuable resource rather than a burden [6].

However, achieving this integration is not without challenges. It requires overcoming barriers such as inadequate infrastructure, technological limitations, financial constraints, and regulatory and policy barriers. Decarbonization strategies entail shifting towards sustainable and climate-neutral technology, while also employing certain fuel technologies as a contingency for renewable energy sources. It is necessary to evaluate various decarbonization technologies for addressing global climate concerns, as well as the impact of strategic policies that support these efforts [7]. Decarbonization approaches with policy measures in the real world require substantial efforts and a mix of policies to achieve near-zero carbon emissions. Policy mixes that incentivize the uptake of low-carbon technologies are projected to be more effective than relying solely on a carbon tax [8]. Combining subsidies for renewables with a residential carbon tax of 50–200 EUR/tCO_2 can lead to near-complete decarbonization [9]. The decarbonization of other sectors such as heavy-duty vehicles, aviation, transportation, industrial production, and natural gas use will require new technologies and policies [10]. Another study highlights the importance of policy adjustments and investment strategies for low-carbon technologies, including wind and solar, to align power sector decarbonization with the carbon neutrality vision [11]. Several techniques and examples of recovery approach have been proposed. For instance, Cheema-Fox et al. [12]

illustrate the financial benefits of decarbonizing a portfolio by creating and examining the performance of different decarbonization strategies in the United States and Europe. Karimi et al. [13] highlight various decarbonization pathways, such as carbon dioxide (CO_2) utilization, efficiency improvements, and non-polluting energy sources, which can be augmented with process system engineering tools. Organschi et al. [14] propose an ultra-fast optimization method for the economic dispatch of thermal generation, emphasizing the importance of decarbonizing existing electricity generation portfolios with renewable resources. Moreover, Lewis et al. [15] focus on decarbonizing industrial emissions, particularly from the cement, lime, glass, and steel industries, and discuss a variety of low-carbon solutions, including carbon capture and storage, fuel switching, and technological change. These examples demonstrate different approaches and some of the sectors involved in decarbonization efforts. The merits and demerits of some of the existing treatments of SW, including pyrolysis, incineration, gasification, landfill, composting, fermentation, and anaerobic digestion (AD), are well discussed [16].

SW decarbonization measures and recommendations have a significant positive impact on solving the climate problem, but there is still a need to assess the role of different decarbonization technologies in mitigating global climate challenges and the impact of strategic policies that support the fight. To achieve this goal, this paper is structured to highlight the challenges of decarbonizing technologies, including the utilization of carbon recycling technologies, and mitigating measures through policy. This review aims to provide a comprehensive analysis of the current landscape, challenges, and strategies for integrating SWM and decarbonization efforts by synthesizing recent research, policy developments, and technological advancements. Finally, this review seeks to inform policymakers, industry stakeholders, and the broader public about the critical importance of this integration and the potential pathways to achieve it.

2. A Brief Overview of Solid Waste Generation Sources and Decarbonization Technologies

2.1. Source of Solid Waste

Modernization and population growth worldwide have led to the overproduction of SW. Currently, only 51% and 16% of SW are recycled in developed and developing countries, respectively [1]. As shown in Figure 1, SW is generated by households, businesses, industries, and institutions. Household waste accounts for more than half of total SW production and includes food waste, paper, glass, metal, plastic, diapers and dirty paper towels, yard waste, and specialty waste such as electronic materials. Commercial waste, which includes commercial formations and private or public marketplaces, is the second largest source of SW after households. Moreover, institutional waste from medical centers, educational schools, prisons, and other government institutions comes as third, while other SW generated by manufacturing sectors or industries comes forth. Improper management of SW, particularly the large quantities left untreated and disposed of in open landfills, leads to significant GHG emissions and other ecological challenges. The primary GHGs emitted from landfills are CH_4 and CO_2, and these harmful gases are released into the atmosphere, contributing to global warming and climate change. Therefore, the impact of GHG emissions on the environment has attracted increasing attention, and it is imperative to reduce their emissions to mitigate the consequences of climate change. Figure 1 illustrates the different sources of SW.

Both high- and low-income countries continue to face challenges in developing appropriate SWM strategies. Urban areas, characterized by high population densities and correspondingly high rates of waste generation, often struggle with limited waste disposal capacity. This inadequate waste management infrastructure plays a significant role in contributing to climate change and the global warming effect. Certain waste management practices, particularly landfilling and incineration, can be considered primary sources of GHG emissions in the SW sector. Landfills, especially those without proper CH_4 capture systems, emit significant amounts of CH_4, a potent GHG. Incineration, while reducing

waste volume, can release CO_2 and other pollutants if not properly controlled. Furthermore, open dumping in developing countries accounts for approximately 93% of SW, while, in developed countries, it account for only 2% [1]. The increase in atmospheric GHG concentrations due to these activities has led to numerous environmental consequences, such as rising sea levels, severe natural disasters, and changes in weather patterns [17]. To mitigate GHG emissions, it is crucial to enhance SW treatment processes, with a focus on carbon recycling. Implementing advanced waste management technologies can significantly reduce the carbon footprint of waste disposal while promoting resource recovery.

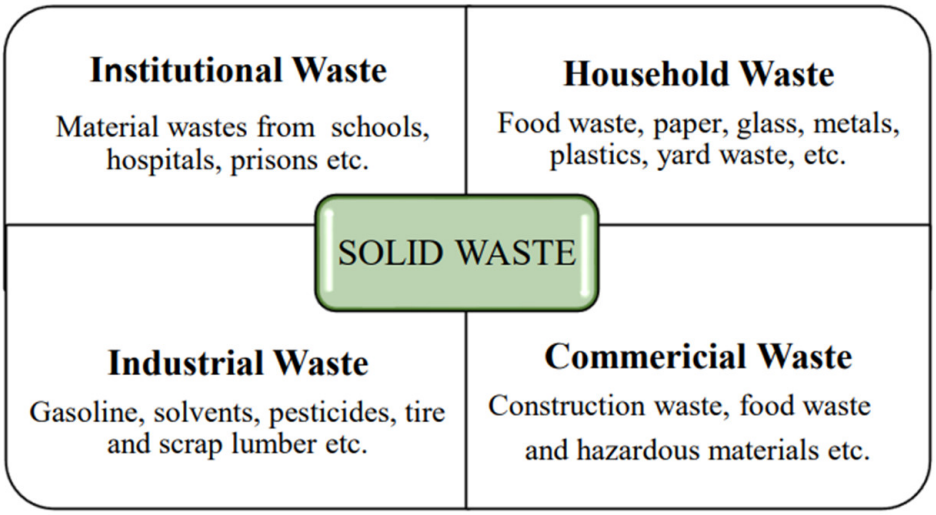


Figure 1. Diagram of solid waste generation sources.

2.2. Environmental Pollution of Solid Waste

Due to the lack of SW treatment facilities in developing countries, about 93% of waste is disposed of in open dumps, while only 2% of waste in developed countries is disposed of in open dumps [1]. This shows that improper handling of SW can lead to large amounts of GHG emissions, which in turn can cause global warming and other related ecological problems. CH_4 and CO_2 are the main gases produced by SW and are reported to be the most significant contributors to climate change [18]. These gases are produced by the anaerobic decomposition of SW in dump sites. CH_4 is a potent GHG, with a warming capacity more than 80 times greater than that of CO_2 within a short time after entering the atmosphere; however, while CO_2 has a more lasting effect, CH_4 determines the rate of warming in the short term. Nowadays, about 30% of global warming is caused by CH_4 [19]. In addition, SW can also contaminate surface water and groundwater, due to leachate generated by open dumping. Some treatment methods, such as incineration, release toxic gases, including sulfur dioxide, nitrogen oxides, and particulate matter, that pollute the environment. These contaminants may cause cancer, cardiovascular disease, and respiratory problems. However, modern incineration facilities are equipped with advanced air pollution control systems to mitigate these emissions. Figure 2 shows the ecological and health challenges caused by SW.

As shown in Figure 2, poor management of SW leads to serious problems for the environment and other organisms. Additionally, SW can lead to heavy metal contamination in water or marine food supplies. Giwa et al. [20] reported that certain bacteria can methylate toxic metals such as mercury, converting inorganic mercury (Hg^{2+}) into methylmercury (CH_3Hg^+). This process occurs primarily in aquatic environments and is facilitated by the gene pair hgcAB, which encodes proteins that catalyze mercury methylation. Methylmercury is a potent neurotoxin that can bioaccumulate in aquatic food chains, ultimately leading to human exposure through the consumption of contaminated seafood. Wei et al. [21] reported that the burning of SW releases harmful gases into the atmosphere and contaminates the soil with heavy metals through its pores. Furthermore, some SW (e.g.,

medical waste) contains viruses, bacteria, and other pathogens that can be spread through poor waste management. The most produced SW is organic material, which can decompose to produce CH_4, significantly contributing to global warming and climate change [19]. Furthermore, SW may contain microbial pathogens that may lead to infections in workers and intimate societies. Based on Mangoro et al. [22], the combustion of SW leads to numerous health challenges, such as allergies, psychological disorders, nose and eye irritation, skin irritation, nausea and vomiting, gastrointestinal issues, and respiratory problems. Other ecological risks associated with SW include neurological diseases, chemical poisoning, and explosive gas emissions [23]. This happens when electronic waste and hazardous waste are mixed with SW.

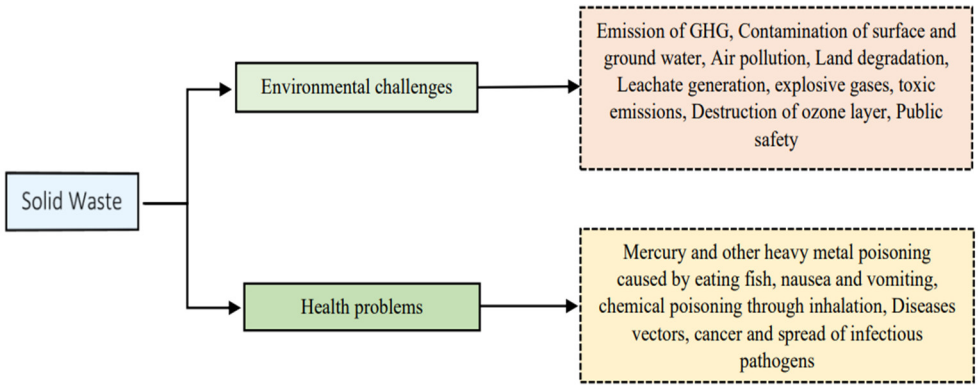


Figure 2. Ecological and associated health challenges caused by solid waste.

The management of SW varies significantly across different economic regions, primarily categorized into developed, developing, and underdeveloped countries. Each category faces unique challenges and employs different strategies, which are reflected in their environmental impacts and management efficiency. In developed countries, SWM systems are generally more advanced, with a significant focus on resource recovery and recycling [24]. Such countries have nearly universal waste collection systems and advanced waste processing technologies [25]. The recycling rate in these regions is relatively high, with countries like Germany and Sweden recycling more than 50% of their waste cycling, as well as having waste-to-energy processes and good landfill management [25]. For instance, high-income countries generate about 34% of the world's waste, despite having only 16% of the world's population [26]. The emission of GHGs is one absolute environmental impact, however, developed countries have systems in place to capture CH_4 from landfills, significantly reducing the potential GHG emissions. Consequently, the per capita waste generation remains high, contributing to greater total emissions compared to other regions. In developing countries, the WM systems in these regions are often overwhelmed by the volume of waste generated. For example, in middle-income countries, only about 48% of waste is collected in cities [27], and a mere 26% in rural areas [28]. Due to the prevalence of open dumping and burning, developing countries contribute significantly to CH_4 emissions, and the improper disposal and treatment of waste can lead to severe health issues and environmental pollution, affecting the water, soil, and air quality. The situation in underdeveloped countries is the most critical, with over 90% of waste often being disposed of in unregulated dumps or openly burned [29]. The lack of infrastructure, funding, and regulatory frameworks severely hampers effective SWM. High levels of CH_4 and CO_2 emissions are due to the prevalence of open burning and the lack of gas capture at dumpsites. The impact on public health is profound, with high incidences of diseases linked to poor SWM. The World Health Organization has highlighted the linkage between SWM practices and health outcomes, emphasizing the need for improved waste management systems to mitigate these risks, and that vulnerable populations, such as children and waste workers, are particularly at risk [30].

2.3. Treatment Technologies of Solid Waste

The type, quantity, and content of SW highly depends on the season, geography, culture, and economic conditions. Due to the large amount of industrial waste in cities, the treatment of rural waste is much easier than that of urban waste. Most of the waste generated in rural areas is organic waste, which can be composted and reused in farm yards and to improve soil properties [31]. In cities, advanced technologies are employed to maximize energy recovery and reduce GHG emissions. SW contains a lot of energy in chemical bonds, which produces high amounts of energy when broken down. Moreover, it was found that integrating SW processing technology offers higher profits in terms of recycling valuable materials, such as electricity, biogas, bioethanol, and value-added nutrients [16]. Using SW to generate energy can have many advantages. For instance, apart from natural gas, GHG emissions from SW energy are much lower than the emissions from energy generated from fossil fuels [31]. To mitigate the environmental impact of GHGs produced by SW, several technologies, including thermochemical (hydrothermal, incineration, and pyrolysis) and biochemical (AD, composting, and fermentation) are applied [32].

Pyrolysis is a well-known method for converting organic and inorganic wastes into syngas, oil, and char by thermal decomposition in an oxygen-free atmosphere. The key process parameters governing pyrolysis include temperature (typically 300–1000 °C), residence time (milliseconds to hours), heating rate (up to 1000 °C/s for flash pyrolysis), and pressure (atmospheric or vacuum) [33]. These parameters significantly influence the product distribution and quality. The pyrolysis process encompasses several intermediate steps, including drying (moisture removal), devolatilization (release of volatile compounds), primary decomposition (breakdown of larger molecules), and secondary reactions (further breakdown and recombination of products). Concurrent with these steps, various side reactions occur, such as cracking (breaking of carbon–carbon bonds), dehydration (removal of water molecules), decarboxylation (removal of CO_2), and aromatization (formation of aromatic compounds) [24]. The process is further influenced by factors like catalysts (enhancing specific reactions or product yields), inhibitors (slowing down certain reactions), feedstock composition (affecting product distribution and quality), and particle size (influencing heat transfer and reaction rates). The primary products of pyrolysis are syngas (a mixture of CO, H_2, CH_4, and other gases), bio-oil (a complex mixture of organic compounds), and char (a solid carbon-rich residue) [24]. The proportion of these products can be optimized by adjusting the process parameters. For instance, fast pyrolysis conditions (high heating rates, moderate temperatures around 500 °C, and short vapor residence times) typically maximize bio-oil yield, while slow pyrolysis favors char production [34].

Incineration is another technique used to treat SW in excessive oxygen supply condition to produce CO_2, CO, water, ash, and other trace chemical compounds. This process has been used to convert SW into energy sources such as heat or electricity and has ecological advantages over landfilling or open dumping [35]. Modern incineration facilities incorporate sophisticated control systems to optimize combustion conditions, minimize emissions, and maximize energy recovery. The primary products of waste incineration are CO_2 and water vapor, similar to other combustion processes. The process of using hot, compressed water to convert waste into syngas, hydro-char, and hydro-oil is hydrothermal treatment [36]. It can process a wide range of feedstocks, including mixed waste streams of biomass and plastics, and operates at relatively low temperatures (typically 180–350 °C) compared to incineration. The process yields a carbon-rich solid product (hydro-char) that can be used as a solid fuel, soil amendment, or precursor for advanced materials [32]. The reaction mechanisms involved in hydrothermal treatment are complex and depend on the feedstock composition and process conditions [37]. For biomass, the process typically involves the hydrolysis of cellulose and hemicellulose, followed by dehydration, decarboxylation, and condensation reactions, while plastics undergo different reaction pathways, often involving hydrolysis, depolymerization, and repolymerization steps [37].

Moreover, organic SW can be treated through AD, which use anaerobic bacteria to decompose waste materials to produce biogas and digestates [38]. In the assessment of the energy generated from waste, the biochemical reactions in AD can be represented by simplified stoichiometric equations, which help in understanding the conversion of organic substrates into biogas components like CH_4 and CO_2. The carbohydrates are converted to glucose, a simple sugar, resulting in equal moles of CO_2 and CH_4. For proteins and fats, the ratios vary based on their specific compositions, but, generally, they produce more CH_4 relative to CO_2 compared to carbohydrates. The Buswell equation provides a more comprehensive method to estimate the biogas composition from the chemical formula of the substrate [39]. This equation is particularly useful for calculating the theoretical yield of CH_4 and CO_2 from a given organic material. These equations and the detailed mechanism of AD provide a framework for understanding how biogas is produced from organic waste, which is crucial for optimizing the process for enhanced biogas production. However, the AD process requires the careful consideration of several critical parameters, particularly the role of methanogenic microorganisms, which are characterized by slow growth rates and high sensitivity to environmental conditions. Additional crucial factors include pH, temperature, substrate type, and composition, as well as operational parameters such as organic loading rate, cultivation methods, and mixing techniques [24].

Composting is the biodegradation of SW and makes a significant contribution to recycling organic waste streams [40], while fermentation treatment is a biological process that converts carbohydrates from SW into bioethanol [41]. Additionally, this process is eco-friendly, with less pollutant emissions. Figure 3 shows the thermochemical and biochemical treatment of SW.

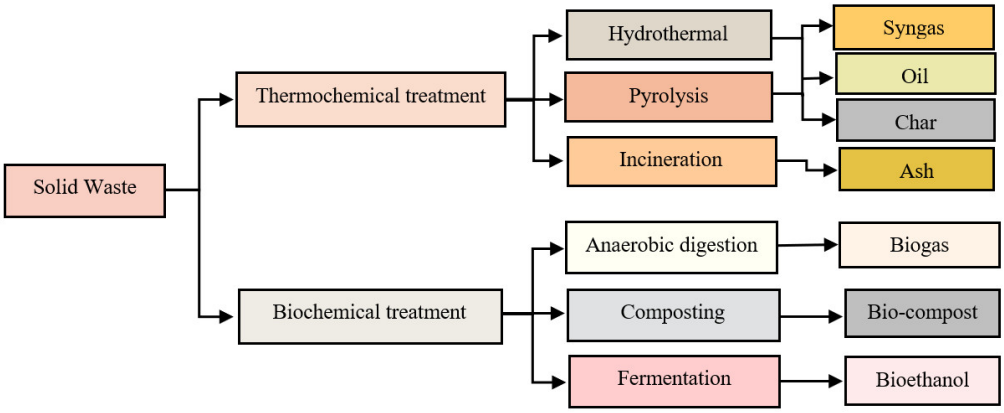


Figure 3. Thermochemical and biochemical treatment of solid waste.

The various treatment technologies shown in Figure 3 are crucial instruments for alleviating the consequences of climate change. Nevertheless, the efficacy of these technologies varies depending on the particular technology, application, geographical area, and type of SW. It is highly recommended to use a combination of these methods and implement them on a large scale to achieve meaningful reductions in GHG emissions. In addition, they not only reduce emissions of hazardous gases, but also promote the recovery of bioenergy and nutrients. For example, syngas and oil generated by hydrothermal treatment or pyrolysis can be used as a good source of hydrogen, electricity, fuel, and heat [16], while char can be employed as an organic fertilizer to improve soil properties or as an additive in other treatment processes, such as AD. In addition, biogas and bioethanol produced from AD and fermentation can be used to produce electricity, heat, and fuel. In addition, digestate or bio-fermented and bio-compost can also be applied in agriculture for soil amendment. The technologies described above offer promising approaches to reduce GHG emissions, enhance bioenergy production and nutrient recovery, and facilitate a shift towards the sustainable treatment of SW.

3. Waste Management Decarbonization Strategies

The integration of waste management and decarbonization strategies is pivotal for addressing environmental sustainability and climate change mitigation. This approach not only focuses on efficient waste handling and disposal, but also emphasizes reducing the GHG emissions associated with waste processes. Waste management encompasses a range of activities aimed at efficiently handling, treating, and disposing of waste generated by human activities. The primary strategies include the following: waste prevention and minimization, recycling and reuse, composting, waste-to-energy (wte), and landfill management.

Decarbonization strategies focus on reducing CO_2 and other GHG emissions in order to mitigate the effects of climate change. In the context of waste management, these strategies include the successful integration of waste management and decarbonization strategies, which requires a holistic approach that considers environmental, economic, and social factors. Policymakers, businesses, and communities must collaborate to implement effective systems that not only manage waste efficiently, but also contribute to the reduction in GHG emissions. This integration can lead to sustainable development, enhanced resource efficiency, and a transition towards a low-carbon economy. Table 1 presents waste management and decarbonization strategies, encompassing technology, regulatory frameworks, and educational approaches, thereby offering insights into their respective merits and demerits.

Table 1. Waste management and decarbonization strategies.

Strategy	Description	Benefits	Shortcomings	References
Waste-to-Energy (WtE)	Conversion of waste materials into energy.	Reduces landfill use, generates energy.	High initial costs, technological needs.	[42,43]
Recycling and Composting	Processing waste to recover materials or decompose organics.	Reduces demand for raw materials, lowers emissions.	Requires segregation, public participation.	[44]
Anaerobic Digestion	Breakdown of organic waste in the absence of oxygen.	Produces biogas, can be used for energy.	Needs controlled conditions, infrastructure.	[24]
Landfill Gas Capture	Collection of methane from landfills.	Reduces GHG emissions, can be used as fuel.	Requires advanced systems, monitoring.	[45]
Regulatory Reforms	Updating laws and policies to support SWM and decarbonization.	Aligns SWM with climate goals, promotes compliance.	Implementation can be complex and slow.	[46]
Public Awareness Campaigns	Education and outreach to promote recycling and reduction.	Increases participation, reduces waste.	Continuous effort needed, cultural barriers.	[47]

MSW primarily comes from households, offices, and commercial establishments such as restaurants and shops. It includes everyday items like product packaging, furniture, clothing, bottles, food scraps, newspapers, and appliances [48]. Effective management strategies for MSW include recycling, which helps to reduce the need for raw materials; composting of organic waste, which turns waste into valuable compost for agriculture; and waste-to-energy processes, where waste is converted into electricity or heat, reducing landfill use and GHG emissions [49]. E-waste consists of discarded electronic appliances such as computers, TVs, and mobile phones [34]. It is one of the fastest-growing waste streams due to rapid tech turnover and electronic consumption. Recycling is crucial for managing e-waste, allowing the recovery of valuable materials like gold, silver, and copper [34]. Proper recycling also prevents hazardous substances in e-waste from harming the environment. Some regions are exploring advanced material recovery facilities to improve the efficiency of e-waste recycling. Ping et al. [34] proposed the sustainable treatment

of spent photovoltaic solar panels using plasma pyrolysis technology and its economic significance as a decarbonization and resource recovery route. They proposed that the technique would promote the resource recovery of valuable materials such as gas, bio-fuel, and immobilized harmful heavy metals. Through plasma technology, after distillation, diesel oil reaches up to 1928 $\times$ 10^3 tons, with an estimated sale profit of electricity reaching up to 21 $\times$ 10^6 MW·h [50]. Moreover, in 2022, the sales profits of pyrolysis oil were USD 34.44 million, and the sales profits of electricity extracted by using diesel oil reached up to USD 1445 million for factories and USD 1020 million for households [34]. Below is a comprehensive table summarizing the different types of SW along with their decarbonization techniques. Table 2 provides an overview of various types of SW and the corresponding decarbonization techniques that can be applied to manage and reduce their environmental impact effectively. It offers detailed insights into waste types, sources, and management strategies, emphasizing the importance of sustainable decarbonization practices in waste management to achieve decarbonization and the sustainable development goals.

Table 2. Specific waste stream types and their applicable decarbonization techniques.

Item	Type of Solid Waste	Sources	Decarbonization Techniques	References
1	Municipal Solid Waste (MSW)	Households, offices, restaurants	Recycling, Waste-to-Energy Incineration, Composting	[51]
2	Industrial Waste	Industrial processes, manufacturing activities	Material Recovery, Waste-to-Energy Processes, Recycling	[52,53]
3	Commercial Waste	Commercial establishments like offices, shops, and restaurants	Recycling, Composting, Waste-to-Energy Incineration	[54]
4	Construction and Demolition Debris (C&D)	Construction, renovation, demolition activities	Recycling, Reuse in Construction, Landfilling	[55]
5	Hazardous Waste	Industries, hospitals, households (e.g., batteries, chemicals, etc.)	Secure Landfills, Chemical Treatment, Incineration	[56]
6	Electronic Waste (E-waste)	Discarded electronic devices and equipment	Recycling, Material Recovery	[34]
7	Agricultural Waste	Farming activities	Bioenergy Production, Composting	[57]
8	Biomedical Waste	Hospitals, healthcare facilities	Incineration, Autoclaving, Chemical Treatment	[58]
9	Radioactive Waste	Nuclear reactors, medical applications	Secure Storage, Containment	[59]
10	Chemical Waste	Chemical manufacturing, industrial processes	Chemical Treatment, Secure Disposal	[56]
11	Plastic Waste	Households, commercial, industrial sources	Recycling, Conversion to Fuel	[60]
12	Organic Waste	Households, food processing industries	Composting, Anaerobic Digestion	[61]
13	Inorganic Waste	Various industrial and commercial processes	Recycling, Material Recovery Facilities	[62]
14	Municipal Services Waste	Street cleaning, parks, beaches	Recycling, Composting, Landfilling	[49]
15	Treatment Plants and Sites Waste	Refineries, power plants, processing plants	Treatment and reuse of by-products, Secure disposal	[63]

4. Decarbonization Challenges

The large-scale process of reducing carbon emissions and transitioning to a low-carbon economy poses several challenges relating to technological, economic, social, and political factors [64]. It requires careful consideration of future technological advancements, economic implications, and policy interventions. The scale of the challenges becomes even more complex when considering the different stages of industrialization associated with various regions [65]. The transition to a low-carbon economy and society requires careful consideration of economic viability. For example, in the UK, the industrial decarbonization challenge focuses on six industrial clusters with high CO_2 production, aiming to transition heavy industry away from fossil fuels using carbon capture and storage and low-carbon hydrogen [66]. On a global scale, retrofitting existing fossil-fuel power plants with carbon capture and storage or biomass has not provided significant emission reductions, highlighting the need for a re-evaluation of existing fossil-fuel power plant abatement [67]. In terms of specific industries, hydrogen has been identified as applicable for decarbonizing anode copper, pig iron, ammonia, methanol, and refinery products, but not aluminum production [68]. Wang et al. [69] compare China, India, and West Europe and highlight the key challenges faced by regions at different industrialization stages. They found that, under a 2 °C target, significant emission reductions are required, and energy structure changes, such as rapid electrification, are necessary. Each of the key decarbonization challenging elements is further highlighted below.

4.1. Technological Challenges

This is mainly due to the high capital and operating costs associated with the construction and operation of carbon capture facilities, as well as the significant infrastructure required for transporting and storing the captured CO_2. While many carbon capture systems have been utilized for an extended period, there are still numerous technological deficiencies that necessitate practical solutions for broader implementation. Recognizing the significance of energy efficiency as a fundamental cornerstone in the pursuit of decarbonization and the fulfillment of sustainable development goals is imperative in light of these obstacles. The level of CO_2 purity in an affluent steam is a crucial factor in determining the carbon separation approach, which remains a barrier in certain systems [70,71]. A common constraint encountered in the carbon capture methods is the efficiency penalty, which is one of the technological challenges detailed in Table 1. This refers to the increase in energy consumption or decrease in power generation that occurs during the implementation of a carbon capture method, as opposed to the situation in which no such strategy is implemented. A typical power plant incurs an efficiency penalty that can vary between 10% and 30%, contingent upon the specific fuel employed [64,71].

4.2. Legal and Political Constraint

Decarbonization efforts are also limited by policy, political, and regulatory constraints at both national and international levels. Inconsistent or inadequate policies regarding carbon pricing, emissions regulations, and renewable energy incentives can impede progress towards decarbonization targets [72]. The absence of a robust political impetus can result in the exclusion of decarbonization from the government's list of priorities. Several global and governmental organizations emphasize the influence of rules and regulations on reducing investment in research and development and encouraging the widespread implementation of carbon capture solutions [64]. Moreover, the lack of cohesive global agreements and frameworks for addressing climate change poses challenges in achieving widespread decarbonization efforts. In addition to the lack of or inadequate political determination, the political structure of a country can occasionally provide some leeway for local or state authorities to determine whether to pursue decarbonization (including carbon capture) based on the local policies and priorities. Local governments in Canada administer community energy and emissions planning programs in accordance with their own local circumstances [64]. Consequently, 72% of the total 279 isolated settlements without

access to the main power grid are currently producing electricity using fossil fuels. These communities continue to depend on hydrocarbons as a result of their plentiful supply and the strong interdependence linked with the decarbonization approach in response to the high energy demand during harsh weather conditions [64,73].

4.3. Economic and Financial Limitation

Another limitation to decarbonization is the economic and financial barriers that come with it. The high initial investment required for transitioning to renewable energy and low-carbon technologies can be a significant deterrent for many businesses and industries. The existing economic infrastructure heavily relies on fossil fuels, and transitioning away from this dependence involves substantial financial risks and uncertainties [74]. Additionally, the socioeconomic impact of decarbonization, particularly on communities reliant on traditional energy industries, is a critical factor that needs to be considered [72]. Presently, the majority of carbon capture systems are in their nascent phases of development. Experts anticipate a decrease in economic obstacles in the future, as the majority of research and development endeavors concentrate on reducing costs and enhancing the financial appeal of these technologies. The key economic challenges in the utilization of captured carbon encompass investment, maintenance, and operational costs. Investing in carbon capture technology necessitates the installation of supplementary equipment and the requirement for more power to operate it. Predictions indicate that the integration of carbon capture technology into a conventional power generation facility could augment the overall investment costs by 50–80 percent, thereby necessitating heightened operational and maintenance expenditures [64,75]. A 22% energy penalty was observed and, consequently, electricity costs have risen by USD 0.5 to 0.7 per kilowatt-hour due to the implementation of carbon capture technologies in coal power facilities in the United States [76]. Upon carbon capture, further expenditures are incurred throughout the carbon capture value chain for transportation, storage, and/or utilization.

4.4. Social Limitations

It is important to recognize that decarbonization efforts are not without social limitations. These limitations encompass various aspects at individual, group/community, and social levels. An immense scale of energy transformation is required to decarbonize the electricity sector by 2050. This paradigm shift necessitates substantial modifications in energy infrastructure, generation, and utilization patterns, all of which are expected to have diverse impacts on communities and individuals [77]. Concerns regarding social acceptability persist in industrialized societies due to the disruptive nature of carbon capture systems, which aim to reshape the industrial paradigm [78]. Additionally, the social acceptance of low-carbon nuclear power plays a crucial role in deep decarbonization pathways, and failure to consider social acceptance can lead to implausible pathways [79]. The integration of decarbonization into electricity markets, while aiming for low-cost decarbonization, may overlook the social and cultural values associated with decarbonization and limit the role of states in managing the trajectory of decarbonization [80]. Conversely, they reject such technologies in other circumstances on account of the exorbitant energy costs that are caused by the inefficiency of certain carbon capture methods [64].

5. Waste Decarbonization Future Perspectives and Outlook

Integrating SWM and decarbonization strategies is crucial for addressing the environmental challenges posed by increasing waste generation and mitigating the impacts of climate change. This subsection presents a comprehensive set of strategies and policies that can be implemented to align SWM practices with decarbonization goals.

5.1. Waste Reduction and Circular Economy Approaches

Adopting circular economy principles is a fundamental strategy for reducing waste generation and promoting the reuse and recycling of materials, thereby reducing the carbon

emissions associated with the production of new materials. There are various key strategies in this domain, including product design and business models, zero-waste strategies, and regulatory measures [81]. Product design and business model design are multifunctional, durable, and easily repairable products; moreover, they promote product–service systems and sharing economies, can extend product lifespans, and minimize waste generation [82]. Product design is a crucial determinant in the waste that products generate throughout their lifecycle. By integrating concepts like "Design for the Environment," products can be made with materials that are easier to recycle, use fewer resources, and are more durable or biodegradable [83]. For instance, designing a product that can be easily disassembled might increase the recycling rate of its components. The use of fewer, less complex, and non-toxic materials can reduce the environmental impact at the end of the product's life. In addition, implementing zero-waste approaches in communities and industries can ensure that all products are recycled or reused, and no waste is sent to landfills or incinerators, thereby reducing GHG emissions from these disposal methods. Zero-waste strategies increase the diversion of waste from landfills and incinerators. This can significantly reduce CH_4 emissions, a potent GHG, from landfills. Over 193 million metric tons of CO_2 equivalent ($MMTCO_2E$) were saved in 2018 through the implementation of various MSW management techniques, including recycling, composting, combustion for energy recovery, and landfilling [51]. The total MSW diverted was around 94 million tons. According to the EPA, this equates to approximately 2.05 $MTCO_2E$ reduced per ton of waste diverted from landfills [84]. Additional measures are Extended Producer Responsibility (EPR) and deposit–refund schemes, which are regulatory measures that encourage waste reduction and support the principles of a circular economy. EPR makes manufacturers accountable for the entire lifecycle of their products, including recycling or disposal, thus motivating them to create more sustainable and recyclable products. Deposit–refund schemes incentivize consumers to return items for recycling by offering a refundable deposit at the time of purchase. Both approaches aim to minimize waste and promote the reuse, repair, and recycling of products, moving away from the traditional linear economy towards a more sustainable model that reduces the environmental impact and conserves resources [85].

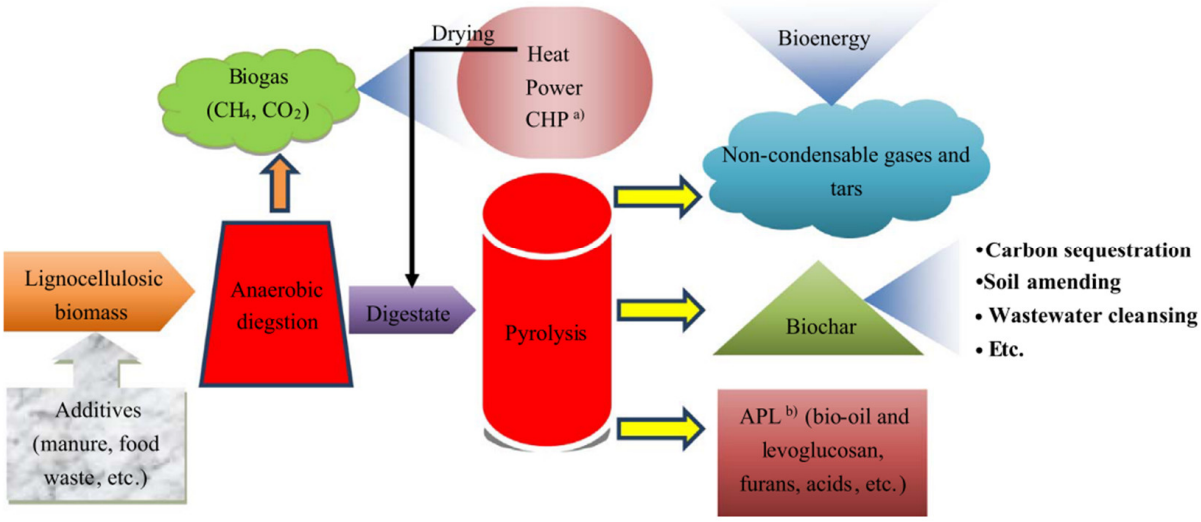
5.2. Waste-to-Energy and Bioenergy Technologies

Waste-to-energy and bioenergy technologies play a crucial role in addressing environmental challenges and energy demands. Various methods, such as biomass gasification, pyrolysis, hydrothermal carbonization (HTC), and AD, are utilized to convert organic waste and energy crops into clean fuels and biogas. These technologies not only help in waste management, but also contribute to sustainable energy production, reducing GHG emissions and the reliance on fossil fuels. Converting organic waste into biogas through AD can provide a renewable source of energy for heating, electricity generation, or as a vehicle fuel, thereby reducing the reliance on fossil fuels [49]. Utilizing incineration, gasification, and pyrolysis technologies to generate energy from waste can reduce the volume of waste requiring disposal while also producing electricity or heat [86]. However, studies highlight the importance of optimizing waste-to-energy pathways to minimize GHG emissions and enhance economic viability, especially in urban and rural communities. Developing nations are also increasingly focusing on waste-to-energy technologies to harness the energy potential of waste materials and reduce the environmental impact, aligning with global sustainability goals. Bioenergy from various biomass sources presents a promising solution to energy security and waste management issues, requiring advancements in supply chain structuring and technological innovations for commercial viability.

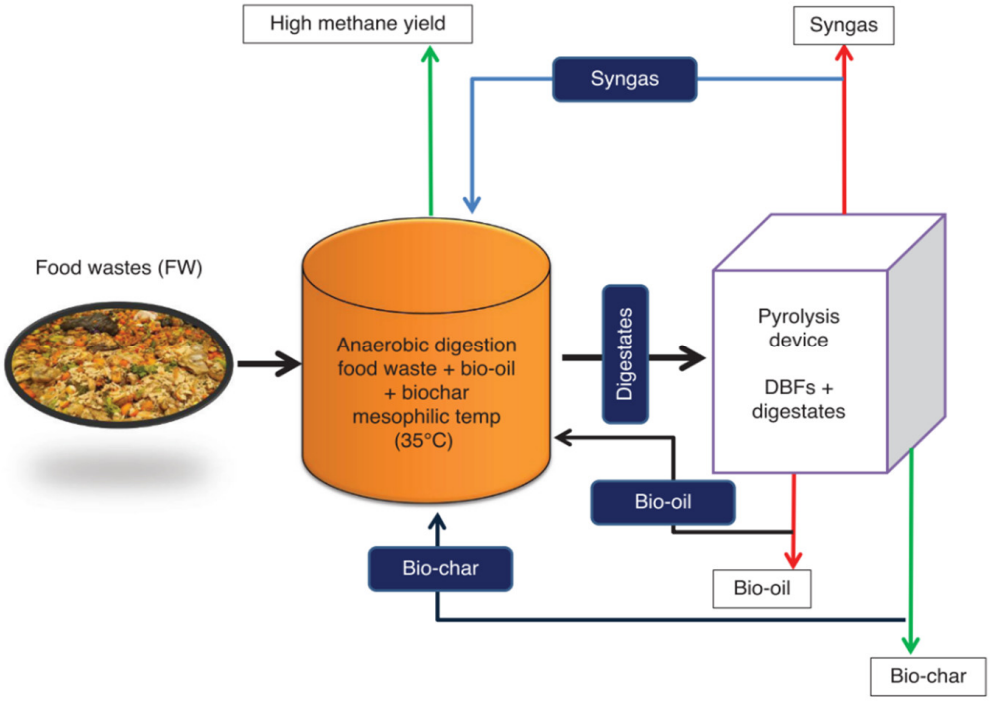
Some researchers conducted an integration of these technologies to enhance the resource recovery values. Giwa et al. integrated pyrolysis and AD in waste valorization, and the concept highlighted the feasibility in a real-life context that the integrated technological routes proposed were capable of valorizing organic waste for maximal resource recovery and sustainable development. They reported that the amount of money saved by processing one ton of date palm waste (another form of FW) through the pyrolysis unit

was about USD 259.58 in Saudi Arabia. Approximately 345,000 tons of date palm waste are processed through the pyrolysis unit each year, and the gross income from the sale of the pyrolysis products made from one ton of date palm waste is USD 556.8, while the cost of producing these pyrolysis products is USD 297.22 [87]. Other integration studies for waste valorization with decarbonization technologies are proposed by [88–90].

Figure 4a–c illustrates the resource recovery of valuable resource materials from waste and the waste-to- energy concept via a different route of decarbonization technology integration.

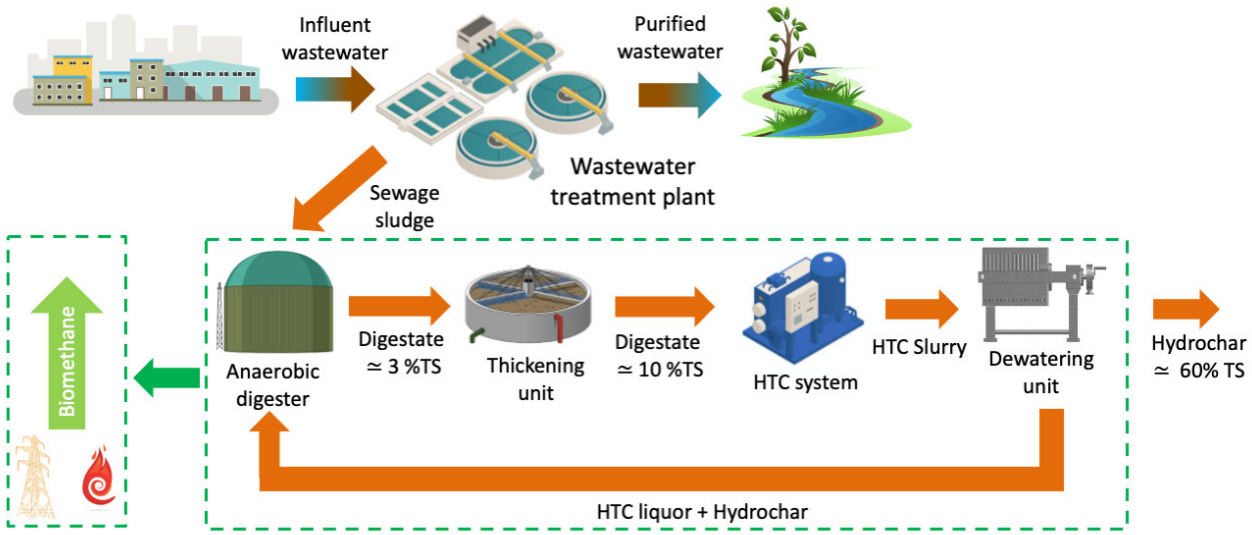


(**a**)



(**b**)

Figure 4. *Cont.*



(**c**)

Figure 4. (**a**): A flow chart of AD-Py. (**a**) CHP: combined heat and power; (**b**) APL: aqueous pyrolysis liquid [88]. (**b**): Schematic route for coupling AD-Py-AD [38]. (**c**): Coupling hydrothermal carbonization with anaerobic digestion for sewage sludge treatment [91].

The integration of AD with thermal processes such as gasification (Gs), pyrolysis (Py), and HTC has been proposed as a promising approach to address the limitations of AD and to enhance resource recovery from biomass and organic waste. Pecchi et al. [32] explored the coupling of AD with these three thermal treatments, considering them as pre- and/or post-treatments for AD. The different scenarios were evaluated separately based on the specific thermal process integrated with AD, as follows: AD-Gs, AD-Py, and AD-HTC. The study discussed the thermal treatment of digestate, the use of char from the thermal process as a stabilizer and enhancer in the AD reactor, and the use of AD of the aqueous products generated from the thermal treatments. Giwa et al. [38] concluded that the integration of decarbonization technologies, such as AD and Py, enables the recycling of byproducts and their complementary utilization, thereby generating beneficial bioenergy, chemicals, and agronomic products from food waste (FW) residues. Furthermore, the combination of AD and Py technologies expands the range of organic feedstocks that can be converted.

Feng et al. [88] highlighted the urgency of addressing climate change and global warming, which are exacerbated by the overuse of fossil fuels, and emphasized the need for the full utilization of renewable bioenergy sources and the practical application of recycling-bioenergy technologies. In their studies on valorizing biomass and organic waste, they proposed AD and pyrolysis as two promising decarbonization technologies for degrading lignocellulosic biomass and producing multiple value-added and renewable bioenergy products. Roberta Ferrentino et al. [91] investigated the coupling of HTC with AD for sewage sludge treatment and reported the influence of HTC liquor and hydrocar on biomethane production. They addressed the integration of HTC and AD processes in wastewater treatment plants. The study examined the enhancement of biomethane yield due to recycling the HTC liquor and hydrocar generated from the digested sludge back to the anaerobic digester. The results demonstrated that, when the HTC liquor was recycled and treated along with the primary and secondary sludge in the AD process, the biomethane yield reached 102 $\pm$ 3 mL CH_4 g^{-1} COD, nearly doubling the biomethane production compared to AD of primary and secondary sludge alone (55 $\pm$ 20 mL CH_4 g^{-1} COD). Furthermore, when both the HTC liquor and 45% of the hydrocar (with respect to the total feedstock) were fed to the AD of primary and secondary sludge, the biomethane yield increased significantly to 187 $\pm$ 18 mL CH_4 g^{-1} COD. Their findings highlight the improvement that the HTC process can bring to AD by enhancing biomethane production

and providing a sustainable solution for treating the HTC liquor and potentially the hydrocar itself.

Economically, these technologies foster job creation in sectors like engineering and facility management, promote energy independence by reducing imports, and can drive socioeconomic development, especially in rural areas. The overall benefits of WtE and bioenergy point to their growing relevance in a sustainable and low-carbon future, with considerable economic opportunities accompanying their deployment and operation.

5.3. Landfill Gas Capture and Utilization

Landfill gas capture and utilization play a crucial role in waste treatment decarbonization by mitigating GHG emissions and generating renewable energy. Landfills are significant sources of CH_4, a potent GHG with a global warming potential over 25 times greater than that of CO_2 [92]. Capturing and utilizing this CH_4 can significantly reduce its environmental impact. Landfill gas capture can abate emissions from up to 90% of the CH_4 generated in landfills, making it a highly effective strategy for reducing GHG emissions [6]. This process converts CH_4 into CO_2, which is less harmful to the atmosphere. The captured CH_4 can be used to produce electricity, heat, or renewable natural gas, providing a reliable and continuous source of renewable energy [93]. This helps to reduce the reliance on fossil fuels and supports the transition to a more sustainable energy system. By capturing landfill gas, harmful pollutants and odors are reduced, improving air quality and health conditions for nearby communities. This also mitigates the explosion hazards associated with CH_4 accumulation. Landfill gas projects can generate economic benefits by creating local jobs, attracting businesses, and providing a cost-effective energy source.

Additionally, these projects can reduce environmental compliance costs by turning pollution into a valuable resource. The technology for landfill gas capture involves installing a network of wellheads and piping systems to collect the gas, which is then processed and either flared or used for energy production. The efficiency of these systems can vary, with closed and engineered landfills achieving up to 85% efficiency, while open dumps are less effective [94]. Despite its benefits, landfill gas capture is considered a second-best waste management strategy, preferable only to landfilling without CH_4 capture. The high costs associated with installing and maintaining gas-to-electricity technologies can be a barrier, although long-term savings and environmental benefits often justify the investment [95]. Additionally, effective management and maintenance of gas capture systems are essential to prevent leaks and ensure optimal performance. Landfill gas capture and utilization are vital components of waste treatment decarbonization [92]. They offer significant environmental, health, and economic benefits by reducing CH_4 emissions and generating renewable energy. As waste management practices evolve, the adoption of landfill gas capture technologies is expected to increase, contributing to global efforts to combat climate change and promote sustainable development.

5.4. Public Awareness and Stakeholder Engagement

SWM decarbonization policy and regulatory frameworks are pivotal in fostering public awareness and engaging stakeholders to actively participate in reducing waste industry emissions. Educational campaigns and public awareness initiatives are essential in showcasing the necessity of individual and communal actions in waste reduction practices, such as recycling and composting, and how these behaviors directly influence climate change mitigation [96]. Increased knowledge among the public can lead to more conscientious waste disposal and consumer habits that align with decarbonization goals. Simultaneously, stakeholder engagement is a cornerstone of effective policy development and implementation. Drawing on the expertise and perspectives of waste management professionals, businesses, non-profit organizations, and policymakers ensures that strategies for decarbonization are both practical and inclusive [97]. Forging partnerships with these groups helps in creating policies that are widely supported and that effectively address the complexities of waste management. Encouraging community involvement

in the decision-making processes further democratizes waste management policies. By incorporating feedback and recognitions from public forums and advisory panels, these frameworks can be customized to address the distinct needs and dynamics of different communities, thereby improving the success rate of the policy initiatives [98]. Additionally, public–private partnerships in the waste management sector are strategic instruments that provide opportunities to leverage the capabilities and ingenuity of the private sector along with the regulatory reach and public accountability of government entities. Such partnerships can spearhead innovation, enhance service delivery, and facilitate investments in waste management infrastructure [99].

Corporate participation is also a strategic area of focus. Through policies that promote social responsibility, businesses become integral in waste reduction efforts, especially when held accountable for the life-cycle impacts of their products. EPR schemes can drive companies to design products that are easier to recycle and less harmful to the environment. An overarching principle in these frameworks is the need for transparency and rigorous reporting. Clear and accessible reporting on waste generation, management practices, recycling rates, and contributions to emissions quantifies progress and reinforces accountability. It not only maintains stakeholder engagement, but also reinforces public trust, ensuring continued support for sustainability initiatives. By integrating public awareness, stakeholder engagement, community involvement, public–private cooperation, and corporate responsibility into the SWM decarbonization policy and regulatory frameworks, a robust, multi-faceted approach is cultivated [100]. This strategic incorporation allows for sustained progress in the complex endeavor of reducing emissions from waste management, thus contributing to the broader objectives of environmental stewardship and climate change mitigation. By implementing these strategies and policies, SWM can be aligned with decarbonization goals, contributing to the reduction of GHG emissions, promoting resource efficiency, and supporting the transition towards a low-carbon and sustainable future.

5.5. Policy and Regulatory Frameworks

Developing robust policy and regulatory frameworks is crucial to support the integration of SWM and decarbonization efforts. The proposed key strategies that constitute the policy and regulatory framework for the SWM decarbonation in this domain are illustrated in Figure 5.

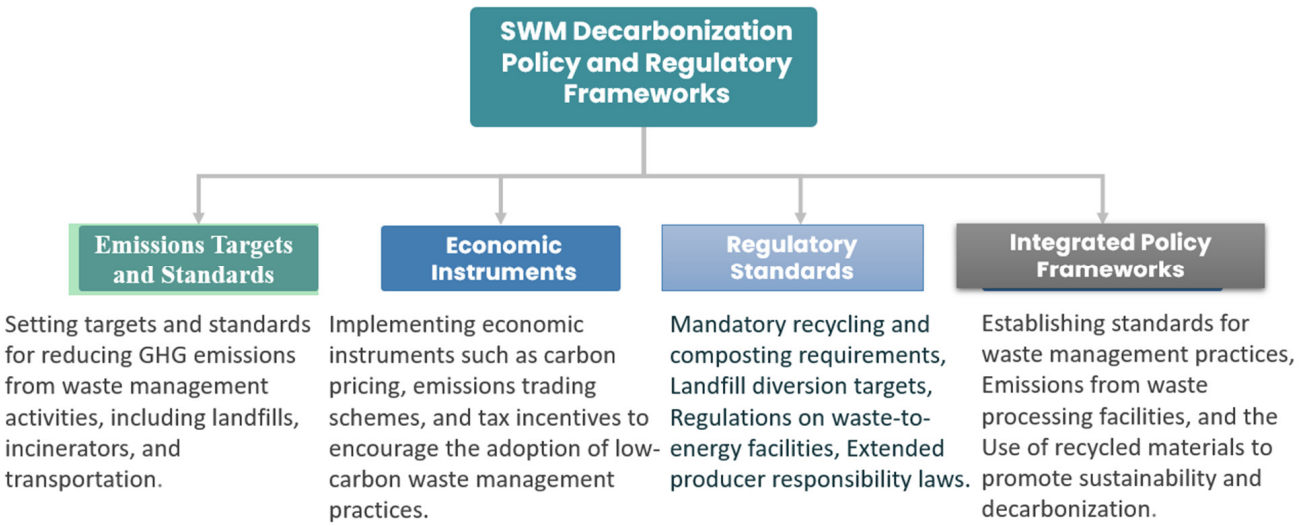


Figure 5. Solid waste management decarbonization policy and regulatory frameworks.

The decarbonization of SWM through carefully crafted policy and regulatory frameworks is a critical step in mitigating climate change. By embedding specific emissions targets and standards into regulations, governments can create a baseline for measuring progress and enforcing compliance. These targets can include caps on GHG emissions from

landfills, incineration plants, and other waste management facilities. While some nations regard incineration as a renewable source of energy, it actually produces a substantial amount of GHGs and air pollutants, thereby shifting subsidies away from more sustainable energy alternatives [101]. In research conducted by Neil Tangri et al. [101], it was discovered that incinerators release more GHGs per electricity unit (1707 g CO_2e/kWh) than any other electricity-generating option, which range from 2.4 to 991.1 g CO_2 equivalent per kilowatt-hour. Additionally, incineration generates higher levels of pollutants compared to other energy replacement sources, including natural gas. Hence, categorizing incineration under 'renewable' or 'clean' energy standards is paradoxical, given that it redirects over USD 40 million in subsidies each year away from cleaner energy sources. The effectiveness of these standards is dependent on reliable monitoring and reporting systems, as well as consequences for non-compliance that are both corrective and a deterrent [102]. Initiatives like landfill-gas-to-energy projects under the Clean Development Mechanism offer opportunities for emission reductions in developing countries, emphasizing the importance of technology transfer and financial support for sustainable waste management practices [103]. Integrating emissions targets and standards into waste management policies is essential for mitigating climate change and promoting a circular economy.

Economic instruments play a crucial role in SWM decarbonization policy and regulatory frameworks by incentivizing waste reduction, proper disposal, and the development of selective collection systems [104]. These instruments, such as payment for environmental services, can attribute economic value to products and services that contribute to environmental quality, benefiting waste picker associations and citizens. Additionally, the integration of advanced technologies and policy instruments in waste-to-energy approaches can optimize waste treatment processes, control costs, reduce carbon emissions, and create job opportunities, contributing to sustainable waste management practices [105]. Aligning with EU waste legislation and investment policies can further enhance municipal SWM by adapting to international standards and implementing successful practices from EU member states. Regulatory standards play a crucial role in SWM decarbonization policy and regulatory frameworks. The integration of effective regulatory and legislative frameworks is essential to address environmental safety and public health concerns, and these frameworks should prioritize waste stream minimization and ensure proper enforcement procedures, legal liability of producers, and verification instruments for waste management practices [106].

Additionally, in the context of radioactive waste management, establishing a robust regulatory framework is vital for ensuring safety, taking into account safety standards based on technical and institutional capabilities. Furthermore, replacing arbitrary models like the Linear No-Threshold Hypothesis with threshold dose-response models can lead to significant cost savings and improved regulatory changes in various radioactive waste management phases. The integrated policy framework in SWM decarbonization policy and regulatory frameworks aims to analyze optimal strategies for SWM systems. This framework integrates various theories in waste management, urban ecology, policy making, eco-innovations, and sustainability to create a theoretical foundation for sustainable cities. Additionally, a proposed online integrated waste management framework streamlines the collection and recycling process, enhancing efficiency and reducing costs [107]. The concept of transformative innovation policy addresses grand challenges and transformative change, emphasizing the need for policy evaluation to reflect these goals, with an integrated evaluation framework proposed to assess system-level impacts and outcomes. Real-world imperfections often lead countries to resort to unconventional policies like capital controls and foreign exchange interventions, highlighting the importance of optimal policy design to address shocks effectively.

Overall, it is through a combination of stringent targets, financial strategies, rigorous standards, and holistic policy integration that the SWM sector can be effectively decarbonized. These approaches, firmly undergirded by policy and regulatory frameworks, are essential for transitioning to a circular economy, reducing global GHG emissions, and

fulfilling international commitments to climate action. Further research is suggested to explore the long-term impacts of these strategies on GHGs, as well as the socio-economic benefits of sustainable waste management practices. Additionally, future studies should assess the replicability of successful models across different contexts, including varying levels of economic development and regulatory environments. Policymakers are advised to incorporate the insights from this research into actionable plans that align with the targets set forth in international climate agreements.

6. Conclusions

The waste sector contributes approximately 5% to global GHG emissions, with the potential to reduce emissions by 2.1–2.8 billion tonnes of CO_2 equivalent annually by 2030 through improved management practices. This paper emphasizes the critical role of SWM as a key component in the broader decarbonization agenda. Despite substantial progress, significant challenges persist in implementing effective SWM decarbonization strategies. These challenges encompass technological limitations, legal and political constraints, economic and financial restrictions, and social barriers. This review highlights several promising approaches to mitigate GHG emissions from waste management, as follows: energy recovery methods, such as waste-to-energy facilities, which can reduce GHG emissions by up to 85% while simultaneously generating renewable energy; enhanced landfill gas capture and utilization technologies with the potential to reduce emissions by 60–90%; and the composting of organic waste, which can decrease CH_4 emissions by 50–80%, while producing valuable soil amendments. This review further emphasizes the need to integrate these SWM decarbonization technologies for enhanced resource recovery and the mitigation of GHG emissions. Furthermore, this study underscores the importance of applying proven frameworks across diverse scenarios, considering various economic conditions and regulatory environments. These frameworks include emissions standards and targets, economic instruments, regulatory standards, and integrated policy frameworks. By incorporating these findings and recommendations into practical strategies, policymakers can align SWM practices with global environmental treaties. This alignment will have the potential to contribute to a 5–10% reduction in overall national GHG emissions through improved SWM practices alone.

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