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Review

Municipal Solid Waste Generation Trend and Bioenergy Recovery Potential: A Review

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Abstract: Finding sustainable solutions to the increasing waste generation in Ghana has received a lot of attention in recent years. Through several waste-to-energy processes, the energy potential of municipal solid waste has recently witnessed significant technological advancements. The Renewable Energy Master Plan has projected the production of about 122 MWp from waste-to-energy installations by 2030 in Ghana. To help policymakers and engineers achieve national goals, this paper reviews the waste generation in Ghana estimated from 2010 to 2030 and the status of various bioenergy technologies in Ghana. This paper further estimates the energy recovery potential of municipal solid waste in Ghana under incineration, anaerobic digestion, and landfill gas recovery technologies. The review establishes that, by 2030, municipal solid waste generation will increase by 123% of the 2023 quantities and may produce 1484.25 MW of installed electricity capacity and 13,002.03 GWh per year, which would amount to nearly 59% of Ghana's 2030 renewable energy target. Additionally, it was determined that anaerobic digestion, incineration, and landfill gas recovery technologies, when properly developed, will add 105.33 MW, 301.4 MW, and 377.31 MW of installed electrical capacity, respectively, to Ghana's energy mix in 2028.

Keywords: bioenergy; Ghana; municipal solid waste; incineration; anaerobic digestion; energy

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1. Introduction

Municipal solid waste (MSW) is produced more frequently due to increased resource consumption driven by an increase in population, the management of which is causing major environmental challenges globally [1]. Unsanitary landfill activities, open dumping, and open incineration methods were frequently utilized in previous years to eliminate municipal solid waste (MSW) without taking into account the potential of MSW for energy production and environmental impact [2]. In recent years, harnessing the energy potential of MSW has seen major advances and technological pushes through several waste-to-energy processes. Waste-to-energy (WTE) plants produce power while lowering the quantity of MSW dumped in landfills [3]. In Ghana, MSW accounts for nearly 80% of all waste generated [4]. Due to rising economic and population growth, people's living standards are changing, contributing to an increase in waste generation in Ghana. Environmental policies governing how waste is to be disposed of are in place in Ghana; however, they have not been put into effect. Therefore, waste can be disposed of at any time and anywhere by individuals [4]. The overall amount of MSW produced nationwide in Ghana has also been influenced by the quick rise of numerous manufacturing businesses within the country's major communities. Although the majority of MSW from the industries is recyclable, the waste is nevertheless disposed of in landfills and incineration sites due to a lack of effective technologies, policies, and funding [4]. The primary cause of climate change effects is the use of non-renewable fuels and the subsequent release of greenhouse gases (GHG), which have an adverse effect on the environment and human health [5]. According to Yaashikaa et al. (2020) [6], innovative technologies that facilitate appropriate waste management pathways are essential to maintaining sustainable development. These technologies have several environmental benefits, such as lowering emissions into the air, water, and soil. A desktop approach was used, where a search of literature with keywords such as municipal solid waste (MSW) generation and bioenergy potential of municipal solid wastes was conducted utilizing Google Scholar, Web of Science, PubMed, and the ScienceDirect database, as shown in Figure 1. The data obtained from 2010 to 2023 were refined based on the following categories: subscribed journals, country (Ghana), article type, publication title, subject area, and access type (open access or achieve). Even though there are a variety of articles available on MSW and its rate of generation for Ghana, the data are limited, as only 26–30 publications have been published from 2010 to 2023, as shown in Figure 1a. This indicates the need to conduct more research on MSW generation estimation. Also, to the best of our knowledge, all of these data on MSW and its rate of generation are rarely reviewed in a single article. The conversion of waste to energy using various bioenergy techniques has been reported to be implemented on small and pilot scales across Ghana. Given the energy demand and municipal solid waste generated in Ghana, this article will critically review MSW and fractions of MSW generations in Ghana, while also comprehensively reviewing the current bioenergy technologies established in Ghana. A total of seven articles were published under the keyword bioenergy potential of MSW in Scopus from 2010 to 2023, as shown in Figure 1b. This indicates that the knowledge of the bioenergy potential of MSW in Ghana is also limited and should be given more attention. This article will also systematically review the bioenergy potential of MSW in Ghana and estimate the energy recovery potential (ERP) of MSW in Ghana under incineration, anaerobic digestion (AD), and landfill gas recovery (LGR) technologies using theoretical ERP equations reported in research works.

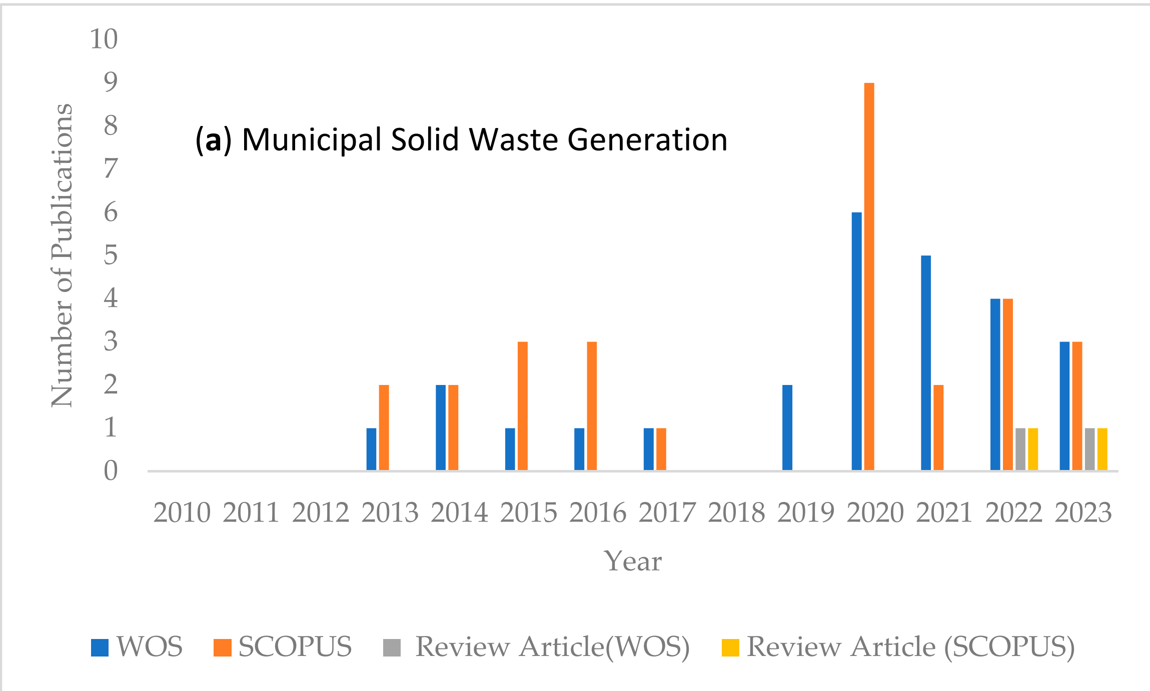

Figure 1. *Cont*.

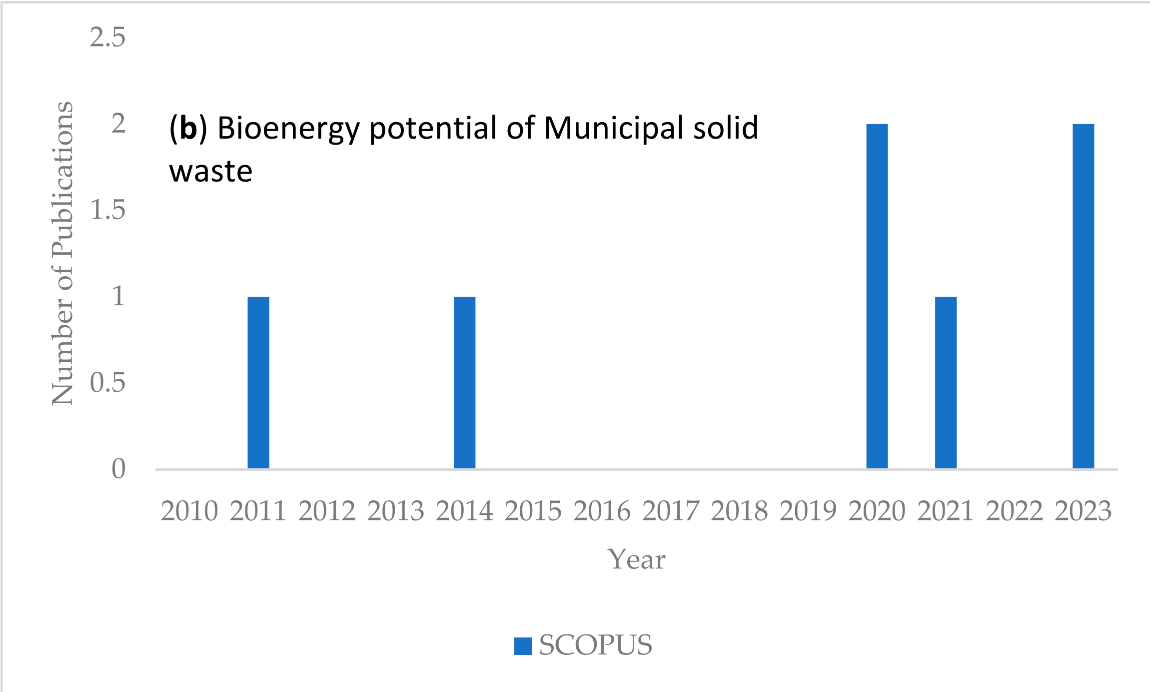

Figure 1. Publication trend of (**a**) municipal solid waste generation and (**b**) bioenergy potential of municipal solid waste from 2010 to 2023 (Web of Science database, 10 November 2023; Scopus database, 10 November 2023).

2. Municipal Solid Waste (MSW)

A variety of solid wastes are regularly disposed of by urban and rural residents as trash. Different municipalities and countries generate municipal solid waste with varying compositions. The differences in lifestyle, economic conditions, industrial structure, and waste management laws are the main causes of the compositional variations [7]. Approximately 2 billion tonnes of municipal solid waste are produced each year around the world [8]. Figure 2 shows the various sources of MSW.

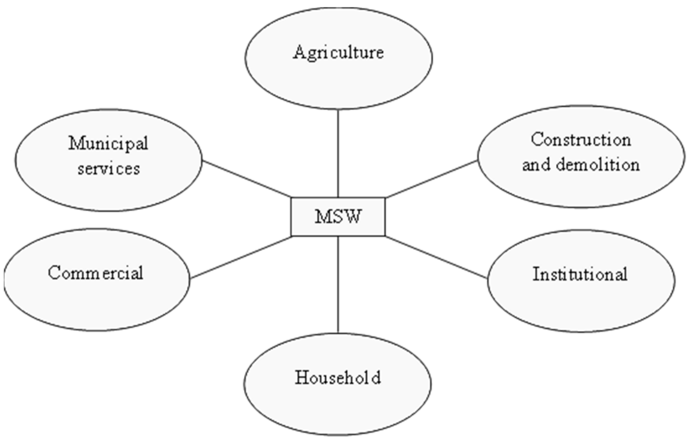

Figure 2. Sources of municipal solid waste [9].

Inappropriate management of MSW has serious environmental and health consequences [10]. MSW can clog drains, contribute to floods during rainy seasons, allow stagnant water to build up, and serve as a mosquito breeding ground in cities and towns [7]. As a result of this, improving waste management is crucial for optimal safety and health [11].

Municipal solid waste management generally involves three stages: (1) waste generation; (2) waste collection, handling, and transfer; and (3) waste disposal, processing, and treatment [8,12]. Waste-to-energy systems are well established in developed nations for converting municipal solid waste to heat and power [13]. In Ghana, in 2022, waste was generated at a rate of 0.47 kg per person per day, or 12,710 tons per day [14], by a population of about 31 million. An enormous amount of the solid waste produced by residents—between 30 and 50%—is not collected for disposal and instead ends up scattered on streets, in sewers, and in streams, where it serves as a breeding ground for pests that spread disease [14,15]. Figure 3 shows that it is estimated that the waste generation in Ghana will continue to increase from approximately 16,581 tons/day to 20,392 tons/day from 2023 to 2030. This translates to a 122.9% generation increment within 5 years [16].

Figure 3. Estimation of MSW generated in Ghana due to population growth.

The organic fraction of MSW (OFMSW) is the world's leading contributor to MSW, accounting for about half of all generated waste [17]. Using the waste composition of 61% organics, 14% plastics, 5% paper, 1% leather and rubber, and 1% textiles in 2015 [18] as a base (shown in Figure 4), MSW compositional generation from 2010 to 2030 was estimated for Ghana from the data obtained from Akrami (2021) [16], as shown in Figure 5. Ghana is known to be a country heavily engaged in agriculture. Most of the produce from agriculture is consumed by the population in Ghana. After consumption, the food waste produced is high, and this is the reason why organic waste has the highest MSW content in Ghana. Unutilized OFMSW produces unutilized methane gas, which contributes to global warming and causes rapid climate change. It is estimated that the organic fraction of MSW in Ghana will reach a generation of approximately 12,439 tons/day by 2030.

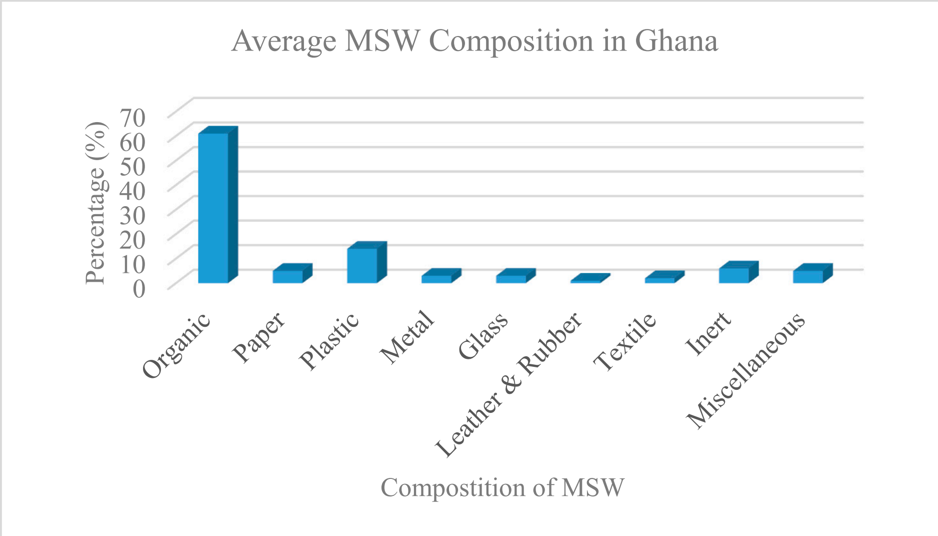

Figure 4. Fractional composition of municipal solid wastes [15].

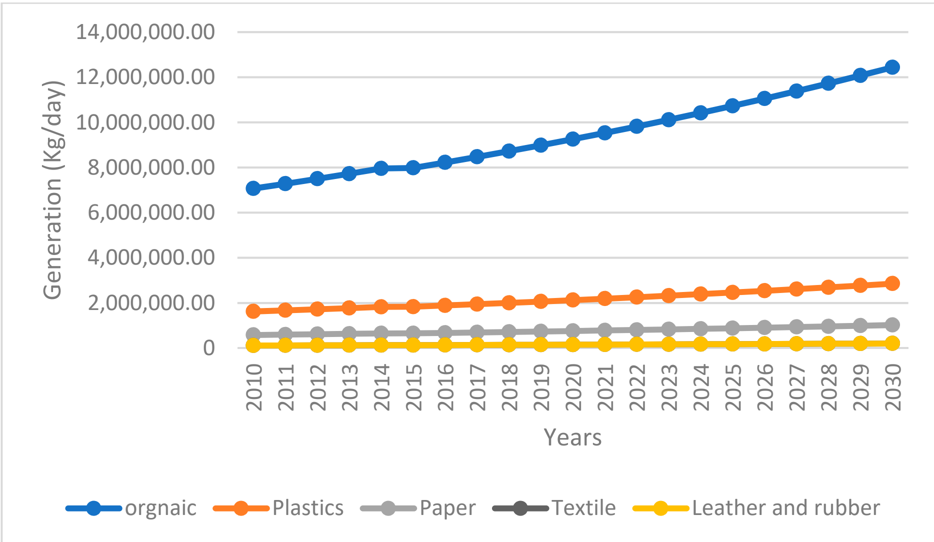

Figure 5. Estimated MSW composition generation in Kg/day. Textile fraction and leather and rubber fraction trends assume the same paths.

The plastic composition of MSW is a major concern in most countries since it is non-biodegradable, poses a threat to aquatic and terrestrial animals, and contributes to environmental pollution [19]. A historical review of plastic waste composition in Ghana's waste stream reveals that the percentage by component was 1.4% in 1979 and had increased to 4% by 1993, and by 1999/2000, the amount of plastic garbage in the waste stream had climbed to 8%, from 5% in 1996/97 [20]. As shown in Figure 4, plastic waste generation was deduced to have increased from 1622.55 tons/day to 2253.72 tons/day from 2010 to 2022 and is estimated to reach 2854.94 tons/day in Ghana in 2030. There is rapid annual plastic waste production because of the wide range of uses for plastics, including throwaway applications, which account for 50% of plastic usage, and medicinal and public health applications [21]; therefore, plastic waste generation might be higher than the estimates shown in Figure 3. Out of all of the MSW in Ghana, in 2015, low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and other plastics had percentage compositions of 2.071%, 3.075%, 3.315%, 1.554%, 0.554%, 0606%, and 2.402%, respectively [18].

Plastics are commonly utilized for product packaging. As a result, packaging materials made of PE, PP, PS, and PVC account for about 50–70% of the total plastic waste [19]. An additional utilization of plastics is in the production of a wide range of useful items, including lightweight and safe components for cars, mobile phones, insulation for buildings, and medical gadgets, among others [22]. Plastic solid waste generated after the initial utilization of plastics is often dumped in landfills around the world, with less than 10% being recycled [19]. Inert fractions of MSW are sand, fine organics, and ash fractions.

Despite the increase in the use of technology, institutions such as schools, hospitals, and others in Ghana utilize paper each day for documentation and other purposes. And since sometimes the utilized papers are of no use, they are mostly discarded as waste, resulting in a high generation of paper waste in Ghana. It is estimated that paper waste generation will increase from 804.90 tons/day to 1019.62 tons/day from 2022 to 2030.

MSW Generation in Selected Urban Cities

The trend of MSW generation in four major cities in Ghana is shown in Tables 1–4. From the tables, it can be seen that waste generation increased with increasing population from the year 2000 to the year 2010 in all the major cities. However, a decreasing trend in the quantity of waste generated per day can be seen from 2010 to 2020. This could be attributed to the recent interest in the collection, reuse, and recycling of certain components of MSW in recent years. Scrap metal collection has, for instance, reduced the composition of metals in MSW in these cities significantly. The use of organic composition as animal feed has also seen some advancement, and a similar trend in the recycling and reuse of plastic has been observed.

Table 1. Population growth and rate of MSW generation in Accra [4,23,24].

Year	Population	Quantity of MSW Generated per Day (×1000 tons)
2000	1,668,000	1.10–1.80
2004	1,815,000	1.25–1.90
2007	1,934,000	1.50–2.20
2010	2,060,000	3.00–3.80
2020	2,514,000	1.05–1.80

Table 2. Population growth and rate of MSW generation in Kumasi [4,18].

Year	Population	Quantity of MSW Generated per Day (×1000 tons)
2000	1,187,000	0.8
2004	1,465,000	0.85–0.90
2007	1,716,000	0.95–1.01
2010	2,010,000	1.50–2.10
2020	3,348,000	2.10

Table 3. Population growth and rate of MSW generation in Takoradi [4,25].

Year	Population	Quantity of MSW Generated per Day (×1000 tons)
2000	294,000	0.60–0.80
2004	373,000	0.70–0.85
2007	445,000	0.90–1.00
2010	532,000	1.30–2.50
2020	946,000	0.66

Table 4. Population growth and rate of MSW generation in Tamale [4,26].

Year	Population	Quantity of MSW Generated per Day (×1000 tons)
2000	205,000	0.35–0.45
2004	259,000	0.40–0.60
2007	308,000	0.70–0.85
2010	366,000	1.09–1.20
2020	642,000	0.46

3. Current Bioenergy Technologies and Waste Management Practices

Every country in the world engages in waste management practices to deal with the rising generation of MSW brought on by the growing population. Waste management techniques can be utilized to generate valuable products from waste, in addition to their core goal of eliminating waste [27,28]. Effective waste management methods commonly employed can be classified into thermal and biological conversion technologies. Thermal conversion technologies include incineration, combustion, gasification, and pyrolysis. Biological conversion technologies include anaerobic digestion, landfilling, and composting. These various technologies are discussed below.

3.1. Thermal Conversion Technologies

3.1.1. Incineration/Combustion

Incineration refers to the waste treatment technology that involves the controlled burning of waste at a temperature of 870–1200 °C (1600 to 2200 °F) for long enough to oxidize approximately 99% of the organic materials in the solid waste and produce high-pressure steam for power generation [4]. Hot combusted gas, an end-product of waste combustion, is generally made up of nitrogen (N_2), carbon dioxide (CO_2), water (H_2O, flue gas), oxygen (O_2), and noncombustible residues [29]. In a heat exchanger, hot flue gases generated from combustion can be used as a hot stream to produce steam from water [29]. The volume and weight of the waste decrease by 90% and 70%, respectively, during incineration [30]. The four major steps of waste-to-energy (WTE) production via incineration are waste pre-treatment, waste combustion, gas scrubbing (including air pollution management), and electricity/steam generation [30]. Incineration works well with non-biodegradable combustible MSW with a low moisture level [31]. Auxiliary fuels are sometimes utilized with MSW during incineration, but this is not required when the waste's lower heating value (LHV) is between 1.000 kcal/kg and 1700 kcal/kg or above [32]. The calorific value of waste may decrease due to the presence of inert waste and its moisture content. As a result of this, the combustibility of MSW is affected, which directly affects the performance of an incinerator [33]. To solve this problem, waste pre-treatment (thermal, mechanical, chemical, and biological) is occasionally used to remove excess moisture content, inert waste, and dangerous substances such as chlorine and mercury [34]. Incinerating a tonne of MSW produces between 36 and 45 kg of oil equivalent (kgoe) [35]. In Ghana, it is projected that about 1000 tons of MSW generated each day in the Kumasi metropolis will be consumed by the WTE incineration plant in the metropolis to produce between 30 and 52 MWh of electricity [4]. The generation of fly ash is a major disadvantage of incineration. An estimated 3–10% of incineration waste is made up of fly ash [36]. This fly ash contains pollutants, including heavy metals and dioxins, which build up in living organisms and have long-lasting detrimental impacts on both human health and the environment [36].

3.1.2. Gasification

Gasification of MSW is a two-stage process that involves the partial combustion of MSW at elevated temperatures in a controlled environment, converting almost all the MSW into gas and char [37]. The MSW is partially combusted in the first stage to yield producer gas (CO_2 and H_2O) and char. The char (or charcoal) chemically reduces CO_2 and H_2O in the second stage to produce primarily carbon monoxide (CO) and hydrogen gas (H_2) [4]. The primary factors influencing the gasification process are temperature, pressure, and oxygen concentrations [38]. For gasification, conditions must include temperatures between 750 and 800 °C and an atmospheric pressure of at least 1 atm [4]. CO, H_2, H_2O, and CH_4 are produced by the gasification process [39]. Syngas constitutes carbon monoxide (CO), hydrogen (H_2), and CO_2 [38]. Syngas is utilized directly to generate energy in gas turbines [35]. Bottom ash is also produced during the gasification process and can be used as road filler material [40]. The gasification method reduces waste by 95% while requiring a less intense cleanup of combustion gases than incineration [41]. It is estimated that the net energy generated by the gasification of a tonne of MSW is between 36 and 63 kgoe [35]. However, MSW has a heterogeneous nature, which makes gasification and syngas purification more difficult [42]. Biomass gasification in Ghana is only currently studied at the plant assessment and research and development stages [43].

3.1.3. Pyrolysis

Various materials, including organics and plastics, can be thermally degraded in an irreversible process known as pyrolysis [44]. Materials subjected to pyrolysis undergo constant changes in their physical phase and chemical composition. Pre-treatment is a crucial step for the removal of glass, inert materials, and metals during pyrolysis. In the initial stage of pyrolysis, the thermal decomposition of pre-treated waste material occurs in an oxygen-free heated chamber at 300 °C [45]. The temperature eventually rises to 800 °C in a non-reactive environment [46]. The primary products obtained via pyrolysis include condensable (tars) and non-condensable volatiles and char [43]. Usually, condensable volatiles (tars) are categorized as liquids (bio-oil). Bio-oil is the most desired intermediate energy carrier due to its purity and stability [47]. Bio-oil can be used in diesel engines, turbines, and furnace/boiler systems [48]. The non-condensable volatiles are primarily gases, such as CO, CO_2, H_2, and C1-C2 hydrocarbons [43]. Biochar, a carbonaceous material, can be processed into activated carbon due to its large surface area [49]. By enhancing nutrient and water retention, biochar boosts the fertility of the soil. Furthermore, using biochar in agriculture reduces the acidity and density of the soil and boosts microbial activity [50]. Pyrolysis can be classified into three types based on the parameters involved in the process: slow, fast, and flash pyrolysis [44], shown in Table 5. Slow pyrolysis is used mainly to produce biochar, while fast pyrolysis primarily produces bio-oil and gas [51], as shown in Table 6. Major factors that influence biochar, bio-oil, and gaseous yields are pyrolysis temperature, MSW size, and heating rate [51]. Catalysts such as nickel and ruthenium-built catalysts, zeolites, and dolomite, when used in pyrolysis, improve the product yield and reduce the energy demand for the process [52,53]. Products from the pyrolysis process most often possess similar properties to fuels. As a result, the pyrolysis of MSW is primarily intended to recover energy. The utilization of the energy products obtained from the pyrolysis process improves the operational efficiency of larger-scale pyrolysis plants [44]. Approximately 45–50 kgoe is generated as net energy via the pyrolysis of a tonne of MSW [54,55]. Additionally, MSW volume can be substantially decreased by pyrolysis by about 84% [32]. The primary limitations of pyrolysis include the following: Utilizing wastes with a high moisture content results in lower net energy recovery; also, it is challenging to burn and transport high-viscosity pyrolysis oil [50]. In Ghana, a pyrolysis plant with a capacity of 6 tonnes was set up to provide an alternative fuel using sawdust as feedstock [56]. This is the only pyrolysis pilot project known to have been established in Ghana, although there have been several laboratory investigations of pyrolysis [57,58]. The projected yields of char and oil of the pyrolysis plant were 25% and 18%, respectively [43]. However, low yields, between 6% and 13%, were attained [43]. This challenge, along with the inadequate feedstock supply and drying and the use of manual process controls, led to the shutdown of the plant [56].

Table 5. Main parameters of pyrolysis process [59,60].

Parameters	Slow Pyrolysis	Fast Pyrolysis	Flash Pyrolysis
Pyrolysis temperature (K)	550–900	850–1250	1050–1300
Heating rate (K/s)	0.1–1	10–200	>1000
Particle size (mm)	5–50	<1	<0.2
Solid residence time (s)	300–3600	0.5–10	<0.5

Table 6. Product yields of the various types of pyrolysis [44].

	Products Yield (wt%)		
	Bio-Oil	**Biochar**	**Syngas**
Slow pyrolysis	10–30	25–65	10–50
Fast pyrolysis	40–70	15–25	10–20
Flash pyrolysis	10–20	10–15	60–80

3.2. Biological Conversion Technology

3.2.1. Anaerobic Digestion (AD)

Anaerobic digestion (or biomethanation) involves the production of biogas and the stabilization of sludge via the microbial decomposition of organic biodegradable matter in the absence of oxygen. Anaerobic digestion degrades and converts the organic components of biodegradable MSW into methane through a series of stages [33]. The first stage, hydrolysis, converts complex organic compounds of MSW, such as carbohydrates, proteins, and fats, to soluble organic molecules such as sugars, amino acids, and fatty acids. During fermentation, the next stage of anaerobic digestion, acetic acid, H_2, and CO_2 are generated through the breakdown of the organic molecules. Methanogenesis is the final stage during which methane forms acetic acid and H_2 [33,38]. Methane is the main component of the biogas produced, coupled with carbon dioxide and traces of contaminants. By removing carbon dioxide, water, and other trace elements, as shown in Table 7, biogas can be converted to pure methane (with a higher calorific value) [42]. Different feed formulation and process parameters, including the organic loading rate, C/N ratio, pH, temperature, moisture content, and retention time, affect the anaerobic digestion of organic MSW [35]. Various temperature ranges, such as 30–37 °C for mesophilic and 50–60 °C for thermophilic anaerobic digesters, are used in AD [42]. Anaerobic digestion processes are classified as "wet" (10–15% dry matter content) or "dry" (24–40% dry matter content) processes [61]. In the wet process, more liquid waste and less solid product are generated. The volume of reactor required for the wet process is less than that required for the dry process [33]. Anaerobic digestion is projected to produce 2–4 times more methane per tonne of MSW in 3 weeks than a landfill does in 6–7 years [62]. Considering 60% organic matter and 40% moisture content, anaerobic digestion of 1 tonne of MSW can produce around 150 kg of methane [63]. Biogas, when compressed, may substitute compressed natural gas in vehicles, where it can power the internal combustion engine or fuel cells [4]. Anaerobic digestion also produces digestate, which is nutrient-rich and can be used to nourish the soil, minimizing the need for mineral fertilizers [64]. Compared to other WTE technologies, biomethanation has the advantages of lower process costs and higher process efficiency (25–30%) [38]. One of the drawbacks of anaerobic digestion is the difficulty of processing wastes with low organic content [59]. In Ghana, several small-scale biogas digesters are in operation [4]. Anaerobic digestion is the most commonly utilized system in Ghana for organic waste (mostly sewage) management, with the gas produced being used for cooking and lighting. Yet because MSW contains varied waste compositions that are not sorted at the source, this technology may not be a viable option for large-scale MSW management and energy generation in Ghana [4].

Table 7. Composition of landfill and digester gas generated from the biochemical conversion of MSW [4].

Composition of Gas	% in Landfill Gas	% in Digester Gas
Methane (CH_4)	55	45–60
Carbon dioxide (CO_2)	45	35–50
Carbon monoxide (CO)	-	0.0–0.3
Nitrogen (N_2)	3.1	1.0–5.0
Hydrogen (H_2)	-	0.0–3.0
Hydrogen sulfide (H_2S), mg/m^3	88	0.1–0.5
Oxygen (O_2)	0.8	Trace
Chlorine (Cl_2), mg/m^3	22	-
Fluorine (F_2), mg/m^3	5	-

3.2.2. Landfill Gas Recovery

Landfilling is the most commonly used waste treatment and disposal method in most nations, particularly in low- and upper-middle-income countries [64]. It is estimated that 70% of all MSW generated worldwide is disposed of in some sort of landfill (sanitary and unsanitary landfills, open dumps) [64]. After the conversion process, all residues from all other available MSW management methods end up in landfills, making landfills a better alternative for MSW management [4]. Sanitary landfilling deals with the regulated disposal of waste on land. Sanitary landfilling minimizes the environmental impact of waste through biogas recovery and leachate treatment [33]. Unsanitary landfilling is frequently employed in developing countries since it provides a simpler and more affordable alternative for disposing of the increasing waste quantity. However, unsanitary landfilling poses a major environmental concern [65]. The organic components of MSW begin to undergo biochemical reactions immediately after MSW is landfilled. Since the surface of the landfill is exposed to atmospheric air, natural organic compounds are oxidized aerobically. This reaction is similar to combustion in that it produces carbon dioxide and water vapor as a result of the process [66]. However, anaerobic digestion is the primary bioreaction in landfills. This reaction occurs in three stages [66]. The complex organic substance is hydrolyzed into soluble molecules by fermentative bacteria in the first step. Acid-forming bacteria, in the second step, convert these molecules to simple organic acids, carbon dioxide, and hydrogen. Acetic acid, propionic acid, and butyric acid are the main acids produced. Lastly, methane is produced in the third stage by methanogenic bacteria. This occurs either by breaking down acids to generate methane and carbon dioxide or by reducing carbon dioxide with hydrogen [66]. Landfill gas (LFG) obtained via landfilling is usually composed of 45–60% methane (CH_4) and 40–55% carbon dioxide (CO_2) [67]. Through a suitable collection and management system, LFG can be trapped, processed, and used as energy as opposed to escaping into the atmosphere [46]. Low-lying marshy land can be transformed into a beneficial area through landfilling [59]. Limitations of landfilling include the risk of contaminated leachate polluting soil and groundwater aquifers when an effective leachate treatment system is absent and that the leachate treatment and pre-treatment of landfill gas to make it pipeline-quality may be expensive [59]. The majority of the municipal solid waste in Ghana gets dumped in unsanitary landfills. However, in some cities in Ghana, engineered (sanitary) landfill sites are utilized for managing MSW [68].

3.2.3. Composting

Composting is the controlled microbial breakdown of organic matter in wet, warm, oxidative, and nonoxidative environments [69]. Compost, an output of composting, has a huge impact on agriculture [70]. This compost is usually pathogen-free and can be used as a fertilizer on farms [71]. Composting also generates heat, water, carbon dioxide, nitrate, sulfate, ammonia, and organic acids [35]. The composting method is the most widely used and cost-effective method for treating the organic component of municipal solid waste [17]. Composting processes are classified into two types: aerobic composting and anaerobic composting [7]. Microbes decompose organic waste in the presence of oxygen during aerobic composting. Oxygen is absent during anaerobic composting [12]. Composting methods can reduce waste by 50 to 85% [72]. Composting has the ability to operate as a soil conditioner, improve the quality of solids, and act as an organic input into agriculture, all while lowering the load on landfills [7]. Composting has some drawbacks, such as the need for an enormous amount of time and a large area of land. Furthermore, when compost generated from unsorted MSW is applied to the soil to increase soil fertility, the soil is more likely to become contaminated with harmful pollutants [73]. Numerous individuals and organizations in Ghana are engaged in the formal or informal production of compost [74].

Vermicomposting

Vermicomposting is a less costly and more environmentally friendly method of managing waste [75]. It is a potential method for organic waste recycling [76]. This efficient technique may convert organic waste and pollutants into high-value products for environmentally friendly soil restoration [77]. Microorganisms, red worms, white worms, and earthworms modify the biochemical structure of organic waste during the vermicomposting process to produce fertilizer [78]. The vermicomposting process is divided into three stages: mixture, digestion, and maturation [79]. The waste component is normally broken down by bacteria and earthworms during the mixture stage. A minimum period of 2–5 days and a temperature of about 15 °C are required at this stage [71]. In the digestion stage, fungi, actinomycetes, and earthworms biodegrade semi-complex compounds into a substrate [80]. A minimum period of 10–30 days and a temperature of about 60 °C are required at this stage [81]. The biodegradation of complex compounds into a substrate takes place in the last and final stage, the maturation and cooling stage [82]. Phosphate-solubilizing bacteria, nitrogen-fixing bacteria, plant growth hormones, and micro- and macronutrients such as Mg, Zn, P, B, Ca, N, and K are present in vermicompost [83]. For composting, a C/N ratio of 30 is favorable since it would result in the production of mature, humified compost [84]. In the field, vermicomposting has had an essential effect on crop development [85]. Vermicompost that is rich in nutrients is produced by earthworms and helps with plant growth [86] in plants such as chili pepper and eggplant [87].

3.3. Ways of Implementing Bioenergy in Ghana

From the above literature, it can be concluded that among thermal conversion technologies, gasification generates the highest amount of energy from MSW, followed by pyrolysis and then incineration. Furthermore, the volume of MSW is reduced by the maximum proportion (95%) during gasification, followed by incineration, and finally pyrolysis. Biochar, a product of pyrolysis, boosts soil fertility and microbial activity. As a result, the pyrolysis process is advantageous for agriculture. Biological conversion technologies are preferable to thermal conversion technologies when the organic and moisture content of MSW is high. The majority of MSW is frequently dumped in landfills. However, with an appropriate leachate treatment system and an effective system for collecting and managing landfill gas, landfilling could be the most common and effective treatment method for MSW. Biogas, primarily produced by anaerobic digestion, is used for energy generation. However, anaerobic digestion would benefit agriculture since the digestate it produces is utilized as fertilizer. Yet it could be deduced that there are no or few implementations of these bioenergy technologies in Ghana, with very small outputs. This is due to social, economic, and security-related obstacles impeding the growth of bioenergy in Africa, including Ghana [88]. Industry Revolution 4.0 technologies hold the opportunity to nullify these bioenergy implementation obstacles or improve the economic feasibility of bioenergy technologies in Ghana. Solid waste management and efficiency could be greatly improved by implementing Industry 4.0 technologies, such as cloud computing, IoT, system integration, smart automation, and cyber-physical systems. With the help of these technologies, real-time data can be generated in both quantity and quality, providing better management and decision-making insights [88,89]. These developments open up the possibility of automating smart systems. Material traceability is improved by RFID and wireless communications, which also help to identify opportunities in the circular economy, including bioenergy technologies [88]. The development of more complex systems, like centralized cloud computing, is made possible by system interconnectivity and automated data transfer, which lower costs by doing away with the requirement for separate computer systems. All things considered, the application of IR 4.0 technologies to waste management holds great potential for streamlining procedures and producing more environmentally friendly outcomes [88,89]. A machine learning (ML)-based optimization system for hydrothermal gasification (HTG) recently developed and purposed to optimize process conditions by taking biomass properties into account [90] could be applied in the implementation of gasification systems in Ghana. This approach is used to automate the optimization of temperature and pressure, two of the many parameters that affect the quality of gasification [91], and to predict gas yield to save time and shorten cycle times [88]. Supervisory Control and Data Acquisition (SCADA) in cyber-physical systems and the internet to automate control processes in municipal plastic waste pyrolysis complexes could be used to optimize and automate pyrolysis plants [92–94] in Ghana and can advance the implementation of pyrolysis plants. Adopting smart technologies to manage composting processes should not be put off any longer, and laws should take into account the possibility of easing the timing restrictions on these processes if they take place under supervision. Additionally, an economic analysis demonstrated that the environment and the community can benefit from investments made towards automating bio-containers in a number of ways [89].

4. Energy Potential of MSW in Ghana

The results presented in Figure 6 show the potential energy that could be generated from MSW collected annually from 2010 to 2030, as estimated by Akrami (2021) [16]. From the results, it can be observed that the energy potential of MSW collected in Ghana in 2010 was 7389.42 GWh of electricity flow, which is equivalent to 843.54 MW installed capacity. From Figure 6, it can be deduced that Ghana's MSW daily generation rate of approximately 19.2 million kg can produce about 35,622 MWh every day. This translates into an annual generation of 13,002.03 GWh and 1484.25 MW in installed electricity capacity, representing about 59% of Ghana's total renewable energy target in 2030, as reported by the Energy Commission (2019) [95].

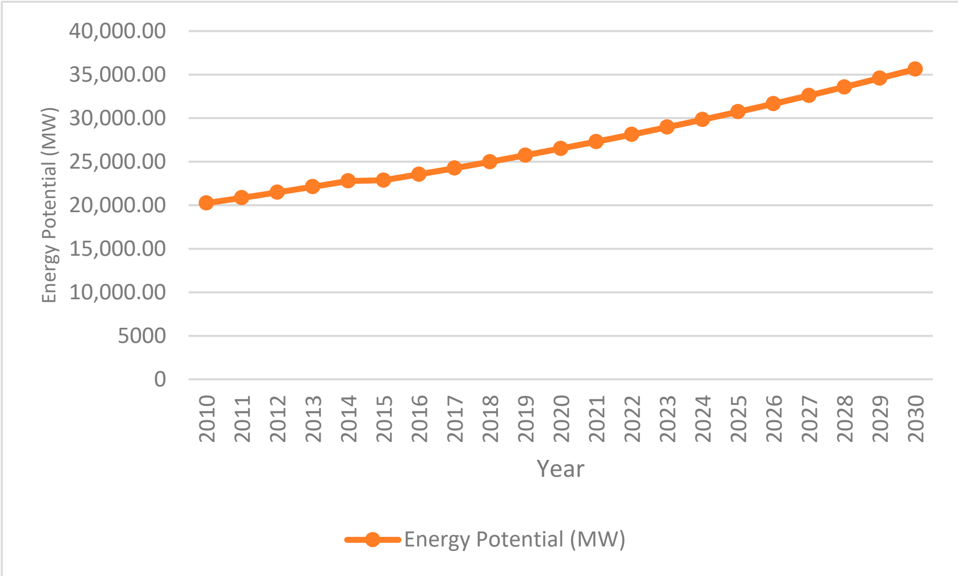

Figure 6. Potential energy recovery from MSW in Ghana.

4.1. Potential Electricity Production from MSW in Ghana under Different Bioenergy Technologies

4.1.1. Potential Electricity Production from MSW under Anaerobic Digestion Technology

The organic fractions of municipal solid waste (OFMSW) are the preferred raw material for anaerobic digestion, which microbes can act on in the presence of moisture. Equation (1) [96] was used to calculate the electricity generation potential of the total OFMSW from 2015 to 2028.

$$ERP_{AD} = \sum_{i=1}^{n} P \cdot W_{PC} \cdot f \cdot M_{OFMSW} \cdot Q \cdot \eta \tag{1}$$

where the components are as follows:

ERP_{AD} = energy recovery potential from anaerobic digestion (MWh/day);
P = population residing at a specific place;
W_{PC} = annual waste generation per capita (T/day);
f = organic matter fraction in solid waste (%);
M_{OFMSW} = generation of methane per ton of OFMSW (Nm^3/T);
Q = lower calorific value of biogas due to methane (MJ/m^3).

Extensive data have been reported on the parameters needed to estimate the energy recovery potential from Equation (1). For this present study, a tonne of MSW can produce 100 Nm^3 of biogas for electricity production [4], assuming 55.5% methane in the biogas [97], 61% OFMSW [18], and a calorific value of 20 MJ/m^3 for methane [98]. The population and annual waste generation per capita were obtained from Figure 2. The efficiency of the anaerobic digestion process in electricity generation, η, is 35–42%, as reported by Uddin and Wright (2022) [99]. This study uses 38.5% efficiency.

Figure 7 details the estimation of electrical energy potential for anaerobic digestion for the 2018–2028 period. Generation in Ghana will increase to 2527.977 MWh/day in the year 2028 as population and waste generation per capita increase per projection.

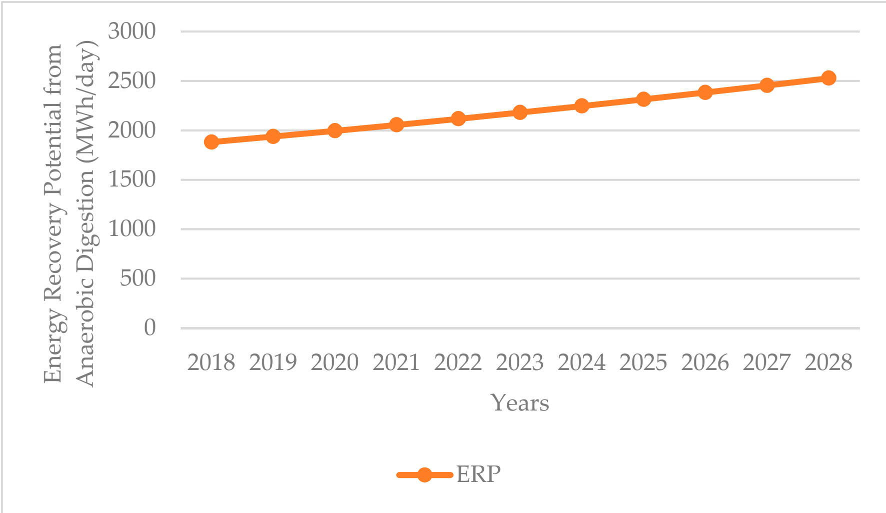

Figure 7. Energy recovery potential from anaerobic digestion (MWh/day).

This translates into an annual generation of 922.711 GWh in 2028 and 105.33 MW in installed electricity capacity, representing about 4.2% of Ghana's total renewable energy target in 2030, as reported by the Energy Commission (2019) [96].

4.1.2. Potential Electricity Production from MSW under Incineration Technology

The organic fractions of municipal solid waste (OFMSW), plastics, paper, leather, rubber, and textiles are the preferred raw materials for incineration technologies, which are combustible. Equation (2) [96] was used to calculate the electricity generation potential that can be obtained from the incineration of municipal solid wastes from 2015 to 2028.

$$ERP_{In} = \eta(M \cdot LCV_{MSW})/1000 \quad (2)$$

where the components are as follows:

ERP_{In} = energy recovery potential from incineration (MWh/day);
M = total mass of dry solid waste (Kg/day);
LCV_{MSW} = lower calorific value of the waste (kWh/Kg);
ŋ = total process efficiency.

For this study, the total mass of solid waste was estimated using the fractional compositions of all the combustibles from Figure 2, adopted from Miezah et al. (2015) [18], a moisture content of 50.5% from the range reported by Kuleape et al. (2014) [100], and a calorific value of 1.67×10^4 KJ/Kg [101]. A total process efficiency of 32% [102] was assumed for these estimations, shown in Figure 6. Figure 8 details the estimation of electrical energy potential for incineration technology for the 2018–2028 period. Generation in Ghana will increase to 7233.36 MWh/day in the year 2028 as population and waste generation per capita increase per projection, translating to 301.4 MW of installed electricity capacity.

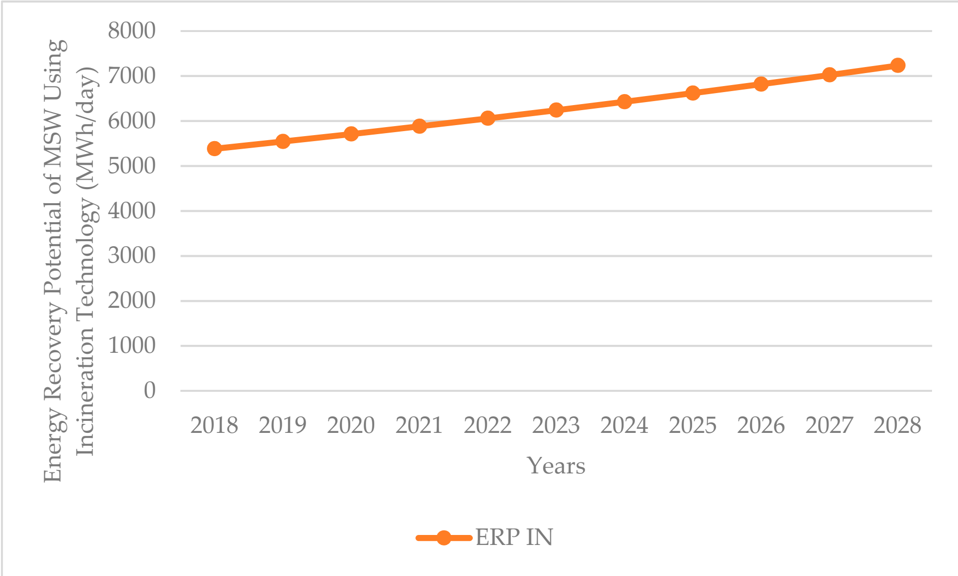

Figure 8. Energy recovery potential of MSW from incineration (MWh/day).

4.1.3. Potential Electricity Production from MSW under Landfill Gas Technology

LandGEM is used to estimate how much landfill gas is collected at dumps [103].

The first-order decay equation is used in this model to determine the methane generation rate. Although it was initially intended to be used by US regulatory organizations, it is currently used on a global scale [104]. The methane produced for a specific year from the collected waste from start to finish, shown in Figure 9, was estimated by LandGEM using Equation (3) [104].

$$Q = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left[\frac{M_i}{10}\right] \left(e^{-kt_{ij}}\right) \quad (3)$$

where the components are as follows:

Q = maximum methane generation flow rate expected;
I = 1-year time increment;
n = (year of the calculation) − (initial year of waste acceptance);
j = 0.1-year time increment;
k = methane production rate (yr^{-1}).

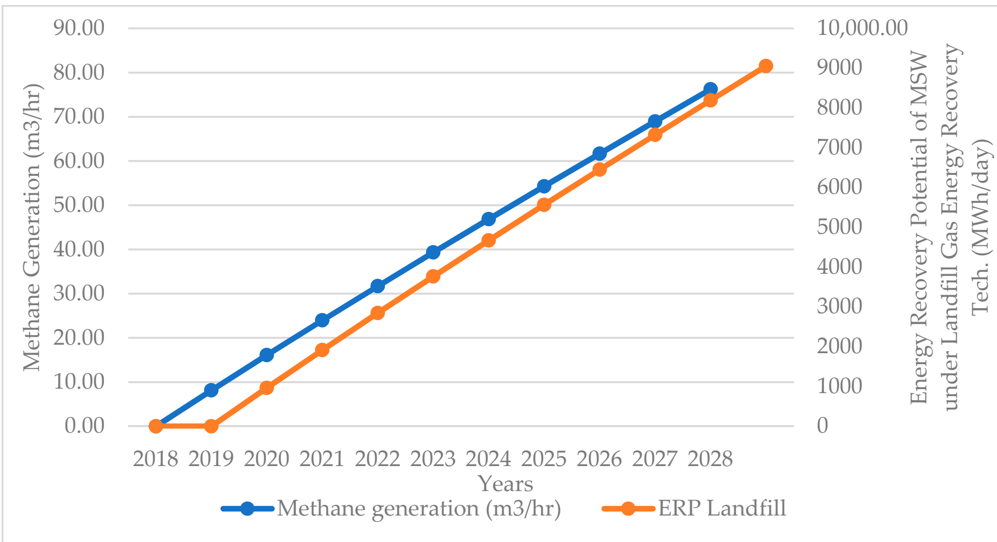

Figure 9. Energy recovery potential of MSW from landfill gas recovery (MWh/day).

The amount of energy recovery potential that can be generated from landfill gas was calculated using Equation (4) [105]. The recovery rates of methane and electrical efficiency were estimated to be 75% and 33%, respectively [105].

$$\text{Electrical energy}(\text{ERP landfill}) = m \times \text{LH}\dot{\text{V}}_{\text{ch4}} \times R \times \eta_{\text{el}} \quad (4)$$

where the components are as follows:

m = mass flow rate of methane (m^3/h);

$\text{LH}\dot{\text{V}}_{\text{ch4}}$ = lower heating value of methane $\left(\frac{\text{MJ}}{\text{m}^3}\right)$;

R = recovery rate of methane = 75%;

η_{el} = electrical efficiency = 33%.

Figure 9 details the estimation of electrical energy potential for landfill gas recovery technology for the 2018–2028 period in Ghana. Generation in Ghana will increase to 9055.42 MWh/day in the year 2028 as population and waste generation per capita increase per projection, translating to 377.31 MW of installed electricity capacity.

4.1.4. Comparison of Installed Electricity Capacity Potentials

The installed electricity capacity potential of MSW under incineration, anaerobic digestion, and landfill gas recovery in the year 2028 has been estimated and compared and is shown in Figure 10. The installed electricity capacity potential of MSW under landfill gas recovery is 377.3 MW, the highest as compared to that of anaerobic digestion and incineration, which recorded 105.3 MW and 301.4 MW, respectively. Therefore, landfill gas recovery would be the most favorable technology for the conversion of MSW to energy, followed by incineration and anaerobic digestion. Furthermore, these technologies could be implemented in a hybrid setup to cover the different fractions of MSW, both biodegradable and non-biodegradable, in Ghana.

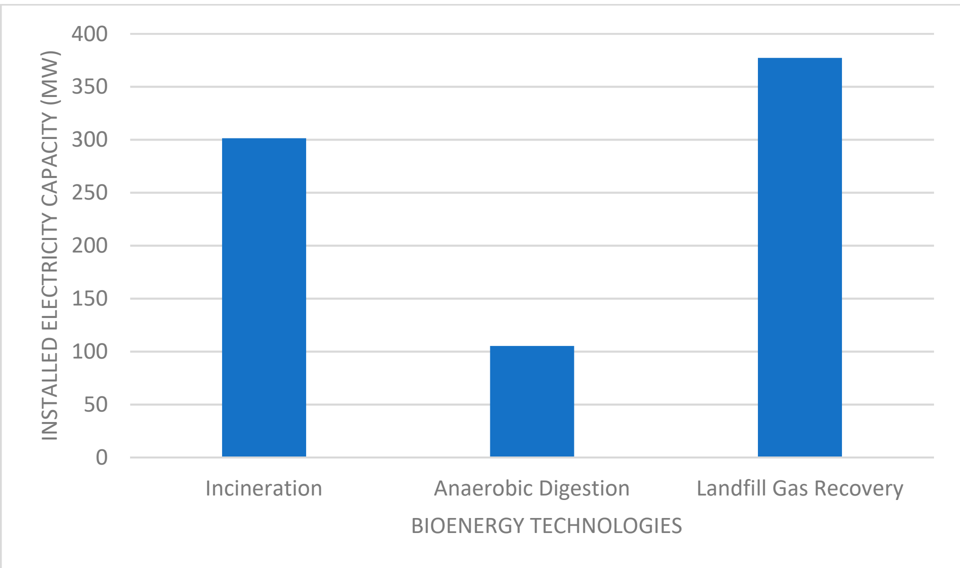

Figure 10. Estimated Installed Electricity Capacity of MSW under Different Bioenergy Technologies in 2018.

4.2. Future Research Scope

Despite the creation of the Renewable Energy Master Plan (REMP) for the production of about 122 MWp from waste-to-energy installations by 2030 in Ghana, the information and data on MSW generation in Ghana are inadequate. This is due to no or very little data collection, research, and legislation on MSW generation and collection, as well as poor waste management structures. This means that more research needs to be conducted on waste management, MSW generation and collection, and the implementation of Industry 4.0 in waste management in Ghana. With this, there will be enough data on MSW available for the government and engineers to make future waste management decisions, especially regarding waste to energy.

5. Conclusions

Due to the steady rise in municipal solid waste creation, which is becoming challenging to manage with traditional trash management approaches, alternative waste management practices have been a hot topic in Ghana in recent years. One such cutting-edge practice that is gaining popularity around the world is the use of municipal solid waste (MSW) for energy production.

Indeed, the Renewable Energy Master Plan (REMP) has projected the production of about 122 MWp from waste-to-energy installations by 2030. This technique is much more commendable because it would not only help to address the issue of waste management in most cities but also create income and aid in bridging the energy gap that the majority of developing nations are struggling with. This review study shows that municipal solid waste generation will increase as population growth in Ghana increases. This will have several repercussions for Ghana if its waste management policies and infrastructure are not improved. Also, this growth of MSW generation could be a great resource for energy generation in Ghana, as this research has revealed that MSW could generate 13,002.03 GWh in a year and 1484.25 MW in installed electricity capacity by 2030, representing about 59% of Ghana's total renewable energy target in 2030. Also, this review estimated the energy recovery potential of MSW under anaerobic digestion, incineration, and landfill gas recovery energy technologies using data reported in existing research works. It was ascertained that in 2028, the energy recovery potential of MSW under anaerobic digestion, incineration, and landfill gas recovery energy will contribute 105.33 MW, 301.4 MW, and 377.31 MW of installed electricity capacity to Ghana's energy mix when investigated and established.

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Data Availability Statement: Data on the estimation of waste generation and collection in Ghana from 2010 to 2030 can be found in Akrami 2021 (https://www.theseus.fi/handle/10024/498959, accessed on 10 August 2023).

Conflicts of Interest: The authors declare no conflict of interest.

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