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Greenhouse Gas Emissions-Based Development and Characterization of Optimal Scenarios for Municipal Solid and Sewage Sludge Waste Management in Astana City

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Abstract: Landfilling is the most applied solid waste management method in developing countries, which leads to a large amount of greenhouse gas (GHG) emissions. It is thus imperative to develop strategies for evaluating different economically viable waste management scenarios to mitigate GHG emissions. According to the Paris Agreement, Kazakhstan planned to decrease GHG emissions by 25% by 2050 as compared to 1990 levels, while reaching carbon neutrality by 2060. In this context, we herein propose four different scenarios for municipal solid waste (MSW) treatment and three scenarios for sewage sludge (SS) treatment with the aim of evaluating the GHG potential for Astana, the capital city of Kazakhstan, using the (solid waste management) SWM-GHG calculator developed by the Institute for Energy and Environmental Research. The MSW treatment scenarios include: (A) 15% recycling of secondary materials and 85% landfilling of remaining MSW; (B) 30% recycling of secondary materials; 70% sanitary landfilling with biogas collection; (C) 30% recycling and 70% biological stabilization and landfilling without biogas collection; and (D) 30% recycling, 20% composting, and 50% (waste-to-energy) WtE incineration. The sewage sludge management scenarios include (1) 100% landfilling; (2) 100% WtE incineration; and (3) co-incineration of sewage sludge and coal. The results reveal that more complex scenarios lead to extensive ecological benefits; however, there are economic constraints. Based on the analysis of the proposed scenarios, we recommend the optimal strategy for MSW treatment to be 30% recycling with biological stabilization that has a total cost of EUR 16.7 million/year and overall GHG emissions of −120 kt of CO_2 eq/year. In terms of sewage sludge management, the addition of coal to sewage sludge simplifies the combustion process due to the higher heat capacity. Considering lower cost and higher energy recovery, it is recommended as a favorable process.

Keywords: municipal solid waste; sewage sludge treatment; GHG emissions; recycling; landfilling; waste management scenarios

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1. Introduction

A sound waste management system is essential for a sustainable environment; a high level of pollution can deteriorate ecosystems and damage plants and animals [1]. However, every country has a different waste management policy and, in particular, post-soviet emerging nations, such as Kazakhstan, have a different approach than the European Union [2]. In 2018, for instance, the municipal solid waste (MSW) disposal rate was over 94%, while the recycling rate was a mere 6% in Kazakhstan [2], compared to the disposal and recycling rates of 23% and 47%, respectively, in the European Union (EU) [3]. Since the disposal in landfills remains the main method of handling MSW in Kazakhstan, assessment of the impact of landfilling on the environment is relevant. The EU is implementing a switch toward a circular economy, intending to keep materials in the loop for as long as possible. In countries such as Sweden, Denmark, Germany, Belgium, Austria, and the Netherlands, solid waste is largely recycled and utilized as secondary raw materials [4]. If recycling is ineffective or impossible, solid waste is used for energy recovery [4]. Nevertheless, if neither of those above-mentioned options is viable, the solid waste is further categorized as acceptable for disposal. González-Sánchez and Martín-Ortega reported that between 1990 and 2017, there was a 23.45% drop in total greenhouse gas (GHG) emissions in the EU from all sectors, including the MSW sector [4]. Over the same period, the overall amount of MSW recycled increased by 13%, while the amount landfilled declined by 60% [5].

Global warming, rising sea level, and changes in seasonal behavior are evidence of climate change [6]. GHGs such as methane, carbon dioxide, and nitrous oxide are the primary drivers of climate change [7]. The waste management sector ranks fourth in terms of GHG emissions after energy, manufacturing, and agriculture [8]. The case of the EU emphasizes the importance of proper waste management in reducing GHG emissions. Different waste management techniques, whether direct or indirect, contribute to GHG emissions to varying degrees. As a result, having an effective waste management plan is critical. For example, in comparison with other treatment alternatives, the disposal of solid waste in landfills without gas recovery and in open landfills generates high amounts of GHG emissions in the form of CH_4, CO_2 and N_2O [9,10]. As reported by Nabavi-Pelesaraei et al. [11], an incineration resulted in lower GHG emissions than landfilling. The authors, based on their case study in Tehran, determined that the process of incineration results in approximately 1642.5 tons of CO_2-eq annually, while the landfilling increased to 92 tons of CO_2-eq annually. Furthermore, Friedrich and Trois [12] showed that gas collection systems in landfills can decrease GHG emissions up to five times. The literature highlights several ways to calculate the GHG emissions emanating from different waste management scenarios, such as landfilling, incineration, and recycling. Devadoss et al. [13] developed a calculator to determine the optimal strategy to treat solid waste in Pakistan. According to their calculations, implementing a strategy with 40% recycling and 32% incineration leads to a balance between the environment and economy. Further, the authors showed that recycling is the best method to significantly decrease GHG emissions; however, it requires substantial financial investments [14]. The study also highlights a need for creating several scenarios and identifying the ecological and financial advantages and disadvantages of each scenario, to recommend the optimal strategy for a country.

In terms of local demographics, proper waste management is critical to meeting the GHG goal set by Kazakhstan. Kazakhstan launched a voluntary commitment campaign in 2010 to reduce GHG emissions by 15% by 2020 and 25% by 2050, as compared to 1990 levels [15]. Furthermore, during the 2020 Climate Ambition Summit, Kazakhstan pledged to achieve carbon neutrality by 2060 [16]. Currently, due to economic constraints, landfilling is the most used waste management practice. Limited studies exist in the literature on analyzing waste management alternatives in Kazakhstan. Abylkhani et al. [17] studied the composition and other properties of MSW generated in Astana, while Inglezakis et al. [18] proposed MSW management techniques and identified low-cost scenarios in Kazakhstan. An in-depth quantitative analysis of GHG emissions is essentially required for Kazakhstan considering the rapid growth of its cities, such as the capital city, Astana.

Significant GHG emissions originate from the wastewater sector in the form of sewage sludge (SS), which has often been neglected in the literature. Due to its high energy consumption and GHG emissions, the sludge treatment process has emerged as a prominent contributor to carbon emissions. According to Astana Su-Arnasy (the wastewater treatment plant, WWTP), 250–350 tons/day of sewage sludge with 70% moisture content are generated in Astana. The current sewage sludge treatment method in Astana city is landfilling requiring extensive areas. A possible alternative method of sewage sludge treatment is incineration, which can reduce the volume of sewage sludge, demolish toxic constituents, and recover energy [19]. Earlier studies on GHG emissions from sewage sludge treatment have been insightful [11,14,18]. Chen and Kuo [20] analyzed the incineration of SS mixture with MSW and estimated the production of 223 tons of CO_2-eq/ton of waste. Furthermore, Zhang et al. [21] analyzed GHG emissions from the incineration of sewage sludge with CaO treatment. CaO was used as an adsorbent to reduce SO_2 emissions during incineration. The CaO-conditioned sludge can also be used in combination with coal for stable combustion, as the SS has a low heating value [21]. These studies are, however, country specific, and the amount and composition of sewage sludge varies significantly. Hence, a similar study on the GHG emissions from the incineration of sewage sludge in Kazakhstan is needed. Given the fast population expansion and continued incidence of landfilling, improvements in MSW and sewage sludge management are imperative. To this end, in this work, four distinct municipal waste management scenarios as well as three sewage sludge management scenarios were proposed and assessed using a GHG calculator in order to determine the optimal waste management scenario to minimize GHG emissions in the capital city of Kazakhstan.

2. Methods and Design of Scenario

The Institute for Energy and Environmental Research (IFEU) has developed the (Solid Waste Management) SWM-GHG tool to calculate GHG emissions and compare different waste management scenarios [22]. This calculator was used to determine GHG emissions in Astana city emanating from the MSW. The SWM-GHG calculator evaluates the net GHG emissions from MSW using credits and debits, wherein credits accounted for avoided GHG emissions, primarily due to recycling, and debits accounted for actual GHG emissions. The major components of MSW for Astana, as determined in our earlier work [17], include 30 recyclables (plastic, paper, metal, glass), organic waste (depending on the season), and the remaining fractions such as textiles, nappies, etc. (Figure 1). The composition of waste was determined by several collection procedures followed by manual sorting [16].

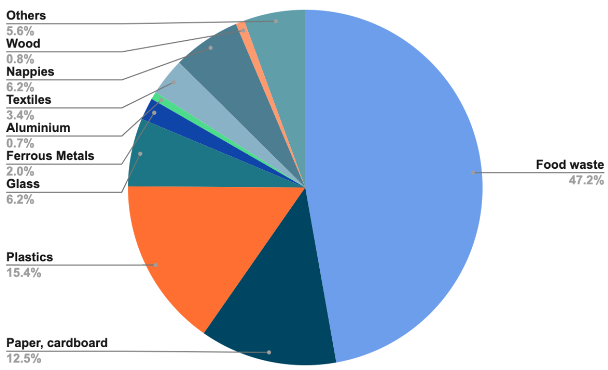


Figure 1. Components of Astana's MSW in percentage of wet waste as determined by Abylkhani et al. [17].

Herein, four scenarios (A–D) for comparison of MSW treatment and three (1–3) scenarios for sewage sludge treatment were created. Scenario A represents the current status quo—15% recycling and 85% landfilling without gas collection. According to Inglezakis et al. [18], 5–6 million tons of solid waste are annually generated in Kazakhstan with an expected increase to 7 million tons by 2030 [23]. In Astana, the current number of recycling enterprises is low, indicating that the MSW largely remains unsorted in Astana [23]. The share of recycled MSW for the third quarter of 2020 amounted to 15.8% [24], supporting the 15% recycling as the base case in our study.

The purpose of Scenarios B and C is to compare landfilling gas collection and landfilling gas collection with biological stabilization (BS), respectively. According to Kazakhstan's "Green Economy" transition concept developed by the Ministry of Energy of the Republic of Kazakhstan in 2018, waste recycling must be increased to 40% by 2030 and to 50% by 2050 [25]. However, recycling rates of 40% by 2030 are unlikely to be achieved. In order to meet the targets as close as possible, scenarios B and C evaluated the separation and recycling of metals, plastics, paper, and glass at 30%. As evaluated by Yay et al. [26], the biological decomposition of MSW produces 442 m^3/t of landfill gas containing 55% of methane. The production of waste to methane is, however, limited due to moisture availability, non-biodegradable fractions, and inaccessible waste, and hence, the actual average methane yield is approximately 100 m^3/t of MSW [27]. Yay et al. [26] further reported that landfilling without gas recovery had GHG emissions of 1840 kg CO_2 eq, while the combination of recycling and sanitary landfilling with gas recovery resulted in 512 kg CO_2 eq/ton annually in Sakary, Turkey. In comparison, herein, the scenarios include only the impact of gas collection during landfilling on GHG emissions at a 70% landfilling rate. Scenario C further extends scenario B with the biological stabilization of the landfilled waste. The BS involves treatment of MSW in aerated compost heaps, with no or minimum mechanical pre-treatment. The described biological treatment occurs for at least 8 weeks followed by waste landfilling.

Scenario D considers an integrated approach to minimize environmental hazards. Herein, the 30% recycling rate involves composting organic waste and incineration of the combustible municipal solid waste. The selection for the scenario was based on the availability of high content of food waste suitable for composting, paper, and plastic fractions in the MSW. Composting leads to significant savings in GHG emissions. For instance, compositing of 71,793 tons of garden waste leads to GHG emissions of 13,282 tons of CO_2 eq/ton; however, in the absence of composting, 93,187 tons of CO_2 eq/ton are released [12]. In addition, material recovery facility (MRF), composting, incineration, and landfilling led to a release of negative 1030 kg CO_2 eq with respect to positive 1840 kg CO_2 eq in the baseline scenario [26]. Therefore, scenario D is expected to have the least GHG emissions among all scenarios.

In summary, the selection of the scenarios was based on the existing situation of Kazakhstan and their potential in the short term. The scenarios include simple treatment methods that are comparatively cheap [28]. Regarding the last scenario, the integrated methods were chosen to show that GHG can be reduced abundantly if more advanced technologies are utilized.

Furthermore, three additional scenarios were developed to identify the additional impact of sewage sludge treatment on GHG emissions. Scenario 1 considers 100% landfilling of sewage sludge, representing the current management practice in Astana. The incineration of SS, considered in scenarios 2 and 3, is becoming the EU's growing disposal technique, rising from 19% in 2005 to 26.9% in 2010, and was anticipated to reach 32% by 2020 [29]. In most cases, incineration is carried out on stabilized and dewatered sludge. The calculation of the total GHG emissions involves the following equations, which have been used earlier in the literature [20]. Furthermore, Table 1 provides a summary of parameters used in GHG calculations using Equations (1) and (2).

$$GHG_{lf} = T \times EF_{el} + \sum m_i \times EF_i + \sum D_i \times EF_{di} \quad (1)$$

$$GHG_{inc} = M \times EF_{GHG_i} + T \times EF_{el} + \sum m_i \times EF_i \quad (2)$$

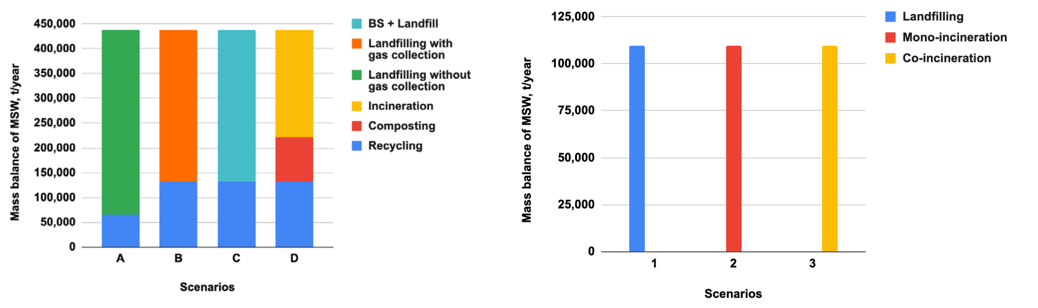
where

GHG_{lf}—GHG emissions from landfilling;
T—the required electricity for the process (kWh/ton);
EF_{el}—the emission factor for a given electricity generation device (kg CO_2-eq/kWh);
m_i—the amount of chemical i used for neutralization (kg);
EF_i—the GHG emission factor attributable to chemical i (kg CO_2-eq/kg);
D_i —the amount of diesel consumption for transportation (L/ton of SS);
EF_{di}—the emission factor of GHGs from diesel consumption (kg CO_2-eq/L);
GHG_{inc}—GHG emissions from incineration;
M—the amount of sewage sludge incinerated (ton);
EF_{GHGi}—the emission factor of GHGs (kg CO_2-eq/ton).

Table 1. The parameters used in GHG calculation.

Parameters	Landfilling	Incineration	References
Required electricity for the process (kWh/ton)	70	200	
Emission factor for a given electricity generation device (kg CO_2-eq/kWh)	0.8095	0.386	[30,31]
Amount of chemical i used (kg/ton)	5.65	45.4	[20]
Emission factor of GHG emissions attributable to chemical i (kg CO_2-eq/kg)	2.51	1.17	[32,33]
Emission factor of GHGs (kg CO_2-eq/ton)	-	6.06	[33]

Scenarios 2 and 3 consider 100% combustion of sewage sludge and co-combustion with coal at 50% wt. along with desulfurization, respectively. As mentioned above, 32.85 kton of dry sludge is generated per year in Astana city. Sewage sludge scenario development is based on the practice of foreign countries that apply monoincineration and co-incineration in waste management. The introduction of coal into Scenario 3 is linked to the fact that Kazakhstan has more reliance on coal. The data for co-combustion of CaO-conditioned sewage sludge and coal were taken from the literature [34]. Incineration of sewage sludge is considered as biogenic since it involves oxidation of organic material [35], and hence, CO_2 emissions resulting from combustion of sewage sludge are not included in the total GHG emissions. According to the Intergovernmental Panel on Climate Change (IPCC) [7], sewage sludge has organic origin and is emission neutral. For instance, in comparison with traditional fossil-fuel energy generation, sewage sludge produces 58% fewer GHG emissions than natural-gas-combined heat and power (CHP) units and 80% less emissions than hard-coal-fired power plants used for district heating systems [29]. While the incineration of pure sewage sludge is carbon neutral, sludge's complex composition and low calorific value makes mono-combustion challenging [36]. Therefore, the addition of a secondary fuel that has higher heat calorific value leads to technically efficient sewage sludge conversion. Zhang et al. [21] have examined the GHG emissions from the co-combustion of SS (with CaO conditioning used for almost complete desulfurization and reduction of N_2O) and coal in the fluidized bed reactor. The N_2O emissions from the combination of 50% CaO-conditioned sewage sludge and 50% coal were found to be 0.758 kg N_2O/kg DS. A summary of the scenarios developed is presented in Table 2, along with the material balance in different scenarios in Figure 2.



(**a**) (**b**)

Figure 2. Material balance under different scenarios (A–D for MSW and 1–3 for SS) developed in this work (**a**) over MSW scenarios and (**b**) over SS scenarios.

Table 2. Description of four MSW and three SS treatment scenarios developed to estimate GHG emissions within Astana.

Scenario	Description	Share, %
	MSW Management	
A	Current situation	15%—recyclables 85%—disposal in landfill without gas collection
B	Source separation and recycling of plastics, paper, metals, glass	30%—recyclables 70%—sanitary landfill with gas collection
C	Source separation and recycling of plastics, paper, metals, glass	30%—recyclables 70%—BS and landfill
D	Source separation and recycling of plastics, paper, metals, glass; waste to energy (WtE) of the residual waste; source separation and composting of the organic fraction.	30%—recyclables 20%—composting 50% of waste to be sent to a WtE plant (incineration)
	SS management	
1	Current situation	100%—landfilling
2	Incineration of SS	100%—incineration
3	Co-incineration of CaO-conditioned SS and coal.	50%—incineration of CaO—conditioned SS 50%—incineration of coal

Among others, methane (CH_4) is one of the most important GHG and can contribute up to 19% to global warming [37,38]. Thus, an accurate amount of CH_4 emissions is essential [39]. CH_4 is produced as a result of bacterial activity, which in turn, depends on the ambient temperature, a factor that has often been neglected in earlier studies. The formation of methane has monthly variations, as has also been shown by Javadinejad et al. [37] using satellite data. The authors showed that with an increase in temperatures during spring and summer, CH_4 emissions increase. The temperature is not the only factor influencing the amount of methane emissions, and there are other factors, including humidity and organic content of the waste, which are beyond the scope of the current work. Data from Javadinejad et al. [37] led to the following relationship, where t indicates temperature (in °C) and Y_{CH4} (in kg/ton of waste) is the methane emissions:

$$Y_{CH4} = 0.887t + 1.789 \times 10^{-3} \quad (3)$$

In this work, the climate factor of the city of Astana was taken into account in order to calculate GHG emissions for a year, as the temperature fluctuations in the steppe are significant. Astana has temperature variations from −30 to +30 °C. Equation (3) was used to calculate the amount of methane emissions during three months of winter in Astana city using the average temperature of −14.3 °C. The amount of methane is inhibited during the winter, and the emissions were computed to be 58,363 and 1079 in kg CO_2 equivalent per ton of MSW and SS, respectively.

Lastly, cost analysis from the developed MSW scenarios was performed using the SWM-GHG calculator. For SS management, the cost was estimated using data from the literature. The energy recovery for SS was calculated using the following relationship [40]:

$$Energy\ recovery(kWh/y) = \frac{NCV \times W \times 1000}{3600} \times 100\% \quad (4)$$

where

NCV—net calorific value (kJ/kg);

W—the dry weight of waste (t/y).

3. Results and Discussion

3.1. Greenhouse Gas Emissions

The net GHG emissions for all scenarios, including MSW and SS, were calculated and are summarized in Table 3 and Figure 3; they also account for seasonal fluctuations. A detailed mass balance and cost analysis as well as credits, debits and net GHG emission calculations are provided in Supplementary Materials (Tables S1 and S2 and Figure S1). Considering MSW management strategies, scenario A represents the current situation in Astana, resulting in the highest amount of GHG emissions of 341.6 kt of CO_2 eq/year. Scenario B, on the other hand, decreases the net GHG emissions by 50%. This indicates that doubling the recycling rate significantly reduces the amount of GHG emissions generated. Implementation of BS in scenario C reduces GHG emissions notably, and no change in recycling rate was applied. The net GHG emissions were much lower in scenario D than the other three cases, having −120.9 kt of CO_2 eq/year. This drastic change was caused by an increase in avoided emissions as a result of incineration and composting. In terms of the amount of GHG emissions generated, scenario D, with more integrated methods included, is the most efficient scenario. The cost estimation will further be considered in the next section.

Table 3. The net GHG emissions per year for MSW and SSW management systems.

MSW Management Scenarios				SS Management Scenarios		
A	**B**	**C**	**D**	**1**	**2**	**3**
kt of CO_2 eq/year				kt of CO_2 eq/year		
341.6	188.5	36.0	−120.9	1.7	−11.0	32.2

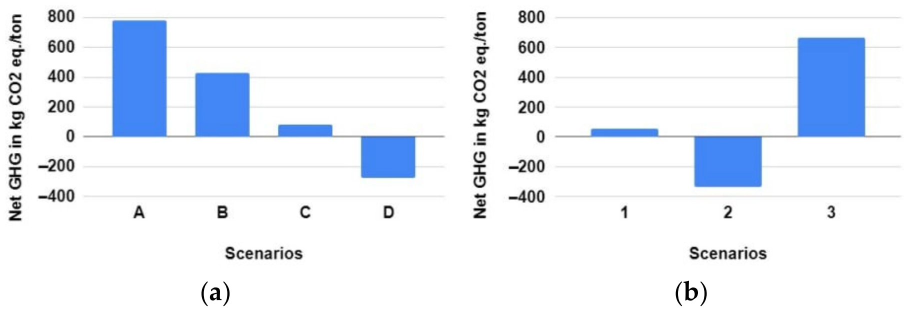


Figure 3. Net GHG emissions per ton of waste for different (**a**) MSW management (Scenarios A–D) and (**b**) SS treatment scenarios (Scenarios 1–3). Follow Table 2 for details of the scenarios.

The sewage sludge management scenarios include landfilling, incineration, and co-incineration. As CO_2 emissions from landfills are derived from biomass, its GHG emissions are not considered. N_2O emissions from landfills are generally negligible [41], and thus, landfilling GHG emissions are restricted to CH_4. The methane emissions for winter were also computed using Equation (1) to be 53.2 kg CO_2 eq/ton. The GHG emissions from transportation were excluded from calculations. Further, the incineration of sewage sludge was investigated in the other two scenarios. Despite landfilling being a favorable technique in Astana city, problems with the land space have become notable. Hence, incineration has to be applied in the near future, as it also has a high potential for energy recovery from SS [42]. The net GHG emissions in Scenario 2 and 3 were calculated using Equations (2) and (3) to be 136.4 and 1530.5 kg of CO_2 eq/tons, respectively. In scenario 2 and 3, the effect of N_2O was considered in calculating GHG emissions with GWP of 265 [41]. Other indirect greenhouse gases, such as NMVOCs, NO, CO, and SO_2, were excluded from calculations since the short lifetime of these gases in the atmosphere, spatial variability, or indirect effects make GHG emissions hard to quantify. The GHG emission from 50% SS incineration resulted in 3300.7 tons of CO_2/year, and GHG from 50% of coal combustion was estimated considering that 1 kg of coal generates 2.86 kg of CO_2 [30]. As a result, net GHG emissions for scenario 3 were high.

However, the energy recovery was considered in scenarios 2 and 3, which led to a significant reduction in GHG emissions. The energy recovery takes into account the calorific values of SS and coal that equates to 11.1 and 30.0 MJ/kg, respectively [43,44]. The energy recovery was calculated using Equation (4). As a result, Table 4 depicts the effect of energy recovery to total GHG emission values in Scenarios 2 and 3, showing that energy recovery for Scenario 3 is higher. The assessment of energy recovery and greenhouse gas emissions from WTE facilities was the sole focus of this study. Considering this, the transport, pre-treatment, and ultimate disposal processes were not examined. Waste minimization and recycling are not the only ways that can reduce GHG emissions, and in terms of SS, energy recovery through the production of energy or electricity can lead to mitigation of GHG emissions [45]. Additionally, an integrated WtE system can result in a large decrease in greenhouse gas emissions and an increase in energy sales revenue [46]. In terms of net GHG emissions, Scenario 2 was found to be the most efficient method, having a negative carbon footprint. A detailed material balance of sludge over different scenarios is presented in Supplementary Materials Table S3.

Table 4. The net GHG emissions per ton for SS management systems with energy recovery consideration.

Scenario	Energy Recovery (10^6 kWh/y)	GHG Emissions, kg of CO_2 eq/tons	Avoided CO_2 Emissions as a Result of Energy Recovery, kg of CO_2 eq/tons	Net GHG Emissions, kg of CO_2 eq/tons
1	-	53.2	-	53.2
2	102.2	136.4	470.9	−334.5
3	188.0	1530.5	866.1	664.4

3.2. Cost Analysis

In order to evaluate the economic aspect of the scenarios, a cost analysis was performed, and the results are presented in Figure 4. The costs for transportation between collection and disposal sites have not been included in the estimation. For different waste treatment methods, different tariffs were considered: landfilling—4 EUR/t, sanitary landfilling with gas collection—16 EUR/t, biological stabilization—23 EUR/t, incineration—70 EUR/t, and composting—10 EUR/t [28,47]. Scenario A obtains the lowest cost due to the low-cost landfilling. Scenario B requires higher costs as compared to the first scenario due to higher costs of disposal with gas collection. Scenario C requires higher costs due to the higher cost of biological stabilization (23 EUR/t) than that of sanitary landfill with gas collection by 7 EUR/t. Figure 4 demonstrates that an increase in scenario complexity leads to a monotonic increase in total costs and a decrease in total GHG emissions. Therefore, considering cost and total GHG emissions from MSW, scenario C has been found to be the most efficient option for MSW treatment in the near future.

In terms of SS management, the reference data for cost estimation was taken from Kacprzak et al. [48]. The average cost of SS landfilling for European countries is 225 EUR/t of dry sludge, while the value is 125 EUR/t of wet sludge for Poland [48]. In the case of Astana, the correlation was made with Poland since the majority of waste management techniques in Poland account for landfilling. In addition, the cost for mono-incineration was 438 EUR/t of dry sludge, and for co-incineration was 100 EUR/t of wet sludge [48]. The cost analysis was performed using the costs of each SS management method and taking into account 32.85 kton dry sewage sludge produced in Astana per year. The cost for scenario 2 is higher than scenario 3 considering the fact that mono-incineration plants require higher operational and investment costs rather than co-incineration plants (Figure 4B) [29]. In particular, the investment and operating expenses per unit mass of SS are higher in smaller plants than in larger plants with a throughput of more than 20,000 MgTS/a (total solids) [49]. Moreover, in less densely populated areas, centralized plants imply higher logistic costs.

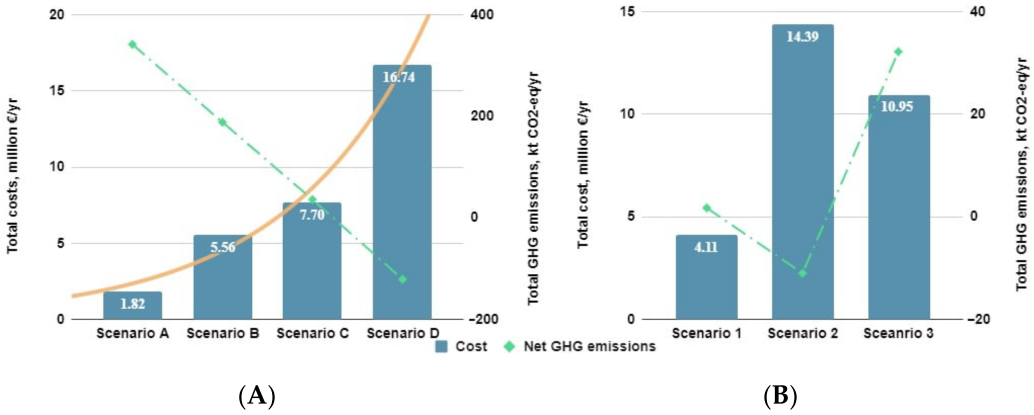


Figure 4. Cost analysis of (**A**) MSW scenarios and (**B**) SS scenarios.

Landfilling is the cheapest method in MSW management, and co-incineration leads to an increase by 6.8 million EUR/yr. Joint analysis of cost and net GHG emissions suggests that scenario 1 is the most affordable method. Scenarios 2 and 3 can be impactful, as they have a potential for energy recovery and avoidance of land space-associated issues. Comparing scenarios 2 and 3, the total GHG emission for Scenario 2 is lower and is recommended considering long-term implications. However, other factors such as (1) low operating cost, (2) high energy recovery potential, and (3) technical efficiency of SS conversion due to higher coal calorific value pushes for Scenario 3.

4. Conclusions

The study investigated GHG emission potentials from four MSW and three SS management scenarios. Astana's waste management strategy is overly reliant on landfilling. Despite advances in waste management laws and regulations, 85% of municipal solid waste is disposed of in landfills. According to the SWM-GHG calculator, 341.6 ktons of GHG emissions in CO_2 eq. were released into the atmosphere, with 15% of the waste recycled and 85% disposed in a landfill. The SWM-GHG calculator assessed three techniques for reducing greenhouse gas emissions from MSW management: landfilling with gas collection, biological stabilization, and an integrated strategy with incineration and increased recycling. The optimal scenario for lowering GHG emissions is to apply BS (Scenario C). For SS, landfilling is the most economical solution. Co-incineration and mono-incineration are both attractive for larger WWTPs. In general, the development and construction of large sewage treatment facilities require prudent and extensive investigation for the feasibility of merging them with a sewage sludge co-incineration facility to maximize synergy effects. The recovered energy from incineration was considered in addition to the GHG calculations. An integrated WtE system can lead to higher energy revenues and a large decrease in GHG emissions. The optimal SS management strategy is scenario 3 considering the significant issues associated with land space allotment, the possibility of energy recovery, and being more affordable compared to Scenario 2. Further alterations in the scenarios need to be investigated. These might include increasing proportions of recycling rates and incorporating other advanced disposal methods such as mechano-biological/physical stabilization, and cement co-furnace. The results presented herein are significant for the civil bodies of Kazakhstan and the CIS region, in general, as it paves a way forward toward efficient waste management and a sustainable future.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142315850/s1, Figure S1: Debits, credits and net GHG emissions in the four MSW scenarios; Table S1: MSW mass balance and cost analysis of the scenarios; Table S2: Debits, credits and net GHG emissions; Table S3: SS mass balance and cost analysis of the scenarios.

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Nomenclature

GHG	Greenhouse Gases
SWM	Solid Waste Management
MSW	Municipal Solid Waste
SS	Sewage Sludge
WtE	Waste to Energy
EU	European Union
IFEU	Institute for Energy and Environmental Research
IPCC	Intergovernmental Panel on Climate Change
WWTPs	Wastewater Treatment Plants
CHP	Combined Heat and Power
BS	Biological Stabilization
MRF	Material Recovery Facility

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