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Research article

Production of gasoline from municipal solid waste via steam gasification, methanol synthesis, and Methanol-to-Gasoline technologies: A techno-economic assessment

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Abstract: A techno-economic analysis of the process of producing gasoline via steam gasification of municipal solid waste (MSW) using dolomite catalysts, followed by a methanol synthesis and a methanol-to-gasoline process (SGMG) was conducted using an Aspen Plus model and an economic assessment. The process includes six steps: MSW pretreatment, steam gasification of MSW to produce syngas, gas purification through CO_2 and acid gas removal, methanol synthesis using syngas, conversion of methanol to gasoline, and gasoline separation. The Aspen Plus model used to estimate the energy and mass balance for sizing the equipment assumed that 2000 dry metric tonnes of MSW per day would be processed. Capital investment required and operating costs of gasoline production were estimated based on the Aspen Plus model's mass and energy balance and an *n*th plant. The minimum selling price (MSP) of gasoline was calculated using the capital investment and operating costs of the process. The total capital investment of the process was estimated to be $148 million, with an annual operational cost of $56 million. The minimum selling price was determined at $2.40/gal for a 20-year project life. The sensitivity analysis showed that the cost of feedstock has a direct impact on the MSP of gasoline, and MSP could decrease to $1.55/gal if the owners of the plant received disposal fees. Increasing the gasoline yield to 0.125 kg of gasoline/kg of MSW decreased the MSP to $1.86/gal. The ash content in MSW played a vital role in estimating the MSP. If the ash content in the feedstock increased, the MSP increased owing to a decrease in the gasoline yield and an increase in the cost of operations.

Keywords: gasification; techno-economic; municipal solid waste; waste management; Waste-to-Energy; syngas

1. Introduction

As environmental awareness and initiatives to decrease societal dependence on fossil fuels (oil, gas, and coal) have increased, biofuel as one of the leading renewable energy resources has gained much attention in the last two decades. According to the Kingdom of Saudi Arabia (KSA) Vision 2030, the government intends to rely on renewable energies to replace fossil fuel energy. Biofuel is a sustainable, clean, and replaceable energy source [1,2]. Energy policies worldwide have promoted the production of clean fuels from biomass or municipal solid waste (MSW) to mitigate climate change [3]. Biofuel is renewable since the biomass from which it is made from is renewable [4]. Agricultural residues, lignocellulose, and MSW are sources of biomass [5]. It has become increasingly important to manage MSW to protect the environment owing to the drastic increase in MSW to be disposed of. For example, China produced 179 million tons of MSW in 2011, and the growth rate in MSW has been 8–10% per year [6].

Municipal solid waste, otherwise known as trash or garbage, is a source of biomass containing, on average, 34% food, 20% paper, 18% plastic, 11% glass, 11% metals, and 6% agriculture waste [4]. Around 1.9 billion tons of MSW are produced worldwide per year, at an average volume of 218 kg per person. Fifty to sixty per cent of MSW (paper, glass, plastic, and metals) could be recycled, and 40–50% of MSW could be used to produce biofuel and energy [6]. The prevalent method of managing MSW to dump it in an open landfill system; a method that has severe health and an environmental impacts since the system is open to the atmosphere [7]. One ecological problem is the pollution released into the air, water, and land since the dumped garbage contains bacteria and insects [8]. MSW also contains chlorinated solvents, aromatic hydrocarbons, vinyl chlorides and heavy metals; burning MSW increases greenhouse gas emissions which are very harmful to human health and the environment, as reported by Magazzino et al. [9]. Furthermore, MSW increases as the population increases, so solutions for decreasing the amount of MSW are required [9]. Furthermore, landfill dumping systems entail costs for maintenance, labor, land, and transportation. However, Magazzino et al. [10] reported that the MSW production is effectively linked with the level of income [10]. As income increases, the standard landfilled process might be replaced by composting, incinerating recycling processes [10].

Globally, MSW is treated using three methods: recycling, thermal treatment, and dumping in landfills [7]. Recyclable material is removed first, and the residual waste used for energy production through thermal treatment processes. Finally, the residue and garbage from the thermal treatment processes are dumped in landfill. The energy production processes are categorized as biological and thermal treatment. Thermal treatment includes the processes of combustion, gasification, and pyrolysis. The heating value of MSW varies from 10 to 20 MJ/kg, which can apply to power generation, fuel transportation, and chemical industries [7]. Hence, MSW has excellent potential to produce energy as is evident in that from 2010 to 2015, around a million metric tonnes of MSW per year was used as feedstock for thermal treatment processes to produce energy [6]. In Europe and Japan, around 350 facilities burn MSW to produce energy. In Switzerland, 8% of MSW is used as feedstock for pyrolysis and gasification processes to produce energy, and some industrial countries produce electricity by burning MSW, and use the ash in the construction of buildings. Some studies have shown that recovering energy as heat or power from MSW using the incineration process is feasible [5,11,12]. However, emissions of harmful acidic gases such as SO_x, HCl, HF, and NO limit the use of the incineration process [13]. The limitations and obstacles of the incineration process have shifted researchers' focus to the gasification process, which, in the last decade, has been widely utilized and commercialized to produce syngas from biomass feedstock [1].

Gasification is a thermochemical process of converting a carbon-containing material into a gaseous product using steam, or air, or a steam and air mixture at high temperatures. Gasification is a process of converting waste to energy (WTE) since it produces less NO and SO_x gas because it works at lower temperatures and reduced conditions [14]. It generates a high syngas yield at temperatures of 600–1000 ℃ with a short residence time (<1 s) [15]. Temperature, pressure, time, reaction conditions, and the type of catalyst are parameters that play a vital role in yielding the products of MSW gasification. Moreover, it is an environmentally friendly process since it produces lower emissions than the combustion process does. Gasification of MSW produces ash, gases such as CO, H_2, CO_2, and light hydrocarbon and char. As reported in previous studies, catalytic gasification of MSW has developed into a promising technology for producing syngas from renewable resources since it meets environmental requirements and produces syngas at a competitive cost. Syngas could be used for ammonia synthesis, methanol production, fuel cell applications, or production of liquid fuel by using the Fischer-Tropsch process [16,17]. Syngas could also be used to generate electrical power [18].

Thamavithya [19] examined air gasification of MSW in a spout-fluid bed reactor at 660 to 770 ℃. The results showed that gasification efficiency increased from 36 to 40%, and tar content in the syngas decreased from 14.47 to 10.98 g/Nm^3 when the reactor's temperature increased from 660 to 770 ℃ [19]. Ponzio [20] also investigated MSW gasification with mixtures of air and steam at 1400 ℃ in an updraft fixed-bed reactor. The study found the syngas yield was 3.4 Nm^3/kg, which indicated the process was promising for generating energy from waste; however, it consumed a large amount of energy [20]. Decreasing the energy requirement is essential and can be done by adding the catalyst to the gasifier, as Luo et al. reported [21]. Luo et al. [21] conducted a series of experiments on steam gasification of MSW to investigate the influence of the reactor temperature on the gas yield. The MSW used included 69 wt% kitchen garbage, 10 wt% paper, 2.1 wt% textiles, 7.4 wt% wood, and 11.5 wt% plastic. The study showed that, as the temperature increased, the syngas yield increased, and char yield decreased. The researchers also examined the effect of adding a dolomite catalyst to the gasifier and found the catalyst enhanced the syngas yield and reduced the tar yield.

Several studies analyzing the techno-economic basis for the production of hydrocarbon fuel from biomass or MSW have been published [2,22–25]. Phillips et al. [22] used an Aspen Plus model to determine mass and energy balances for a techno-economic assessment of large-scale steam gasification, followed by methanol synthesis and a methanol-to-gasoline process (SGMG) to produce gasoline from biomass. As per their model, they found that the MSP for the gasoline in 2007 was $1.95/gal [22]. Hannula [24] conducted another techno-economic analysis to produce gasoline from biomass via the SGMG process and developed an Aspen Plus model for the process. The model results showed that the minimum viable selling price for the biofuel was $7.35/gal [24]. Although several techno-economic analyses of processes for producing biofuel from biomass via thermal treatment have been published, a techno-economic assessment of the use of MSW as feedstock for the SGMG process to produce gasoline has not been published or investigated in previous studies. Thus, this study develops a techno-economic assessment to evaluate the feasibility and economic potential of producing gasoline from MSW via the SGMG process.

Aspen Plus software was used to determine the energy and mass balance for the model in this study. The results of the Aspen Plus model were used to calculate the capital investment and the cost of operations, and a discounted cash analysis method was applied to estimate the MSP of the gasoline produced. Finally, sensitivity analyses were performed to evaluate the influence of financial and model assumptions on the MSP.

2. Process design

The overall process flow diagram to produce gasoline from MSW via the SGMG process is shown in Figure 1. The gasoline production plant used in this simulation process was assumed to process 2000 dry metric tonnes (DMT) per day of MSW in a six-step process: MSW pretreatment, gasification, gas purification, methanol synthesis, conversion of methanol to gasoline, and gasoline separation.

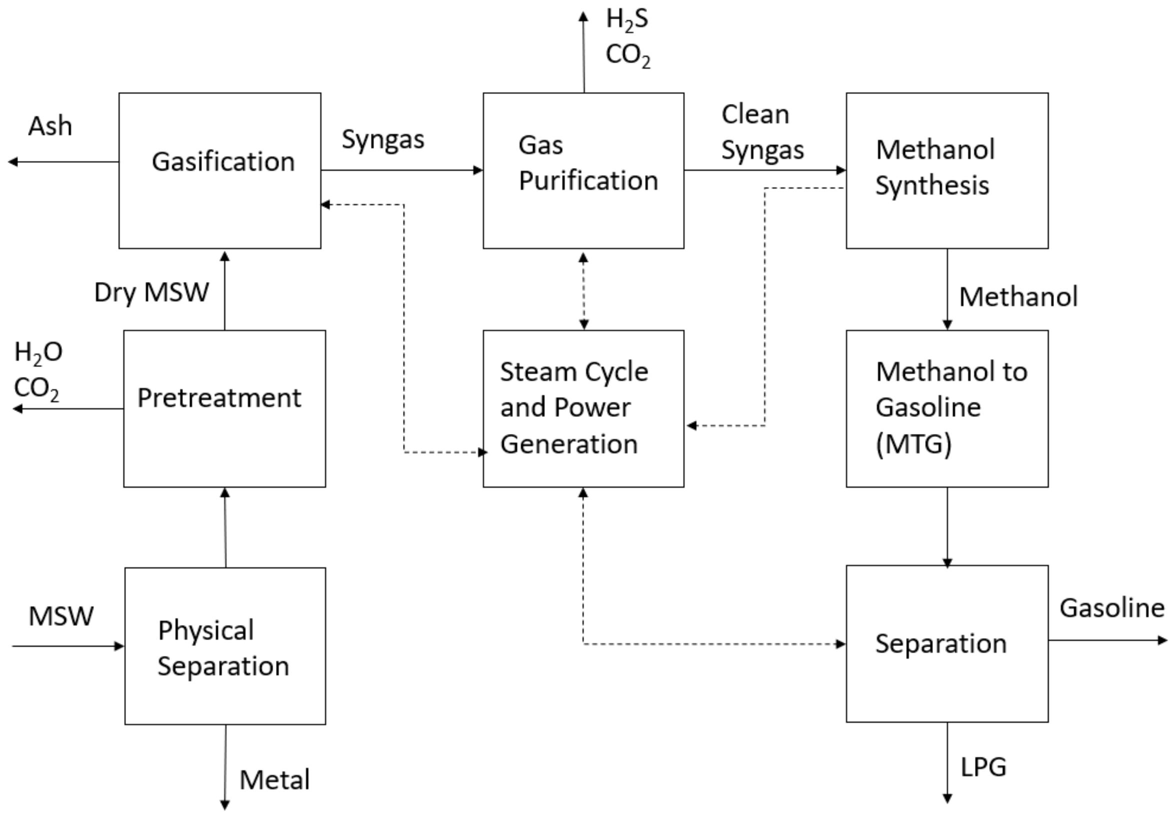

Figure 1. The overall process flow diagram of gasoline production via the SGMG process.

2.1. Municipal solid waste pretreatment

The moisture content of the MSW was assumed to be 30% after the metal and ceramic were separated out. Next, the MSW was treated using a two-step process, grinding the waste to reduce the size of the pieces and drying it to remove the moisture. The MSW was crushed to 1–2 mm particles using a hammer mill. The grinding process consumed 15 kWh of energy per metric tonne (MT) of MSW. Once ground, the MSW was transferred to the dryer to reduce the moisture content of the feedstock to 10%. The energy requirement for the drying step was approximately 45 kWh/MT of MSW [22,26]. After the MSW was crushed and dried, the gasification process began.

2.2. Gasification

A dual circulating fluid bed steam gasifier was selected for MSW gasification at 880 ℃ and 1.59 bar of pressure. Olivine and magnesium silicate were used as the catalysts for the gasification reaction and to supply heat to the gasifier by circulating between the gasifier and char combustor [22]. The steam-to-feed ratio was 0.7 kg of steam per kg of MSW [21], with the steam for the gasifier supplied by the steam cycle and power generation unit [22]. During gasification, MSW was converted to a syngas containing a mixture of gases (CO, H_2, CO_2, CH_4) and char. The product yields were 68.1 wt% syngas, and 31.9 wt% char. The syngas was sent on to the gas purification process. A cyclone was applied to separate the char, olivine, and ash from the gases, and the olivine was heated before being recirculated to the gasifier. Using 20% excess air in the char combustor to increase the olivine's temperature to 980 ℃ rendered the char combustible. The heat balance between the char combustor and gasifier was reached by controlling airflow to the char combustor and olivine circulation rate [22]. The products of the char combustor were separated using a pair of cyclones [22], the first of which was designed to capture the olivine, and the second one to capture the ash to be sent to a landfill for disposal. The hot olivine was recycled to the gasifier as both a heat carrier and catalyst [22,26].

2.3. Gas purification

The gas purification process was designed to clean and condition the syngas before the methanol synthesis. The syngas was treated in two steps: acid gas (CO_2 and H_2S) removal and low-temperature shifting [24]. The hot syngas was cooled using heat exchange with the steam cycle and water scrubbing. The scrubber is designed to remove impurities, such as particulates and ammonia. The scrubber water was sent to an off-site wastewater treatment facility. Before CO_2 removal, the syngas was compressed to improve the efficiency of the process and decrease energy consumption. After the syngas had been compressed, it was fed into the amine-based acid gas removal system (AGR) to reduce CO_2 and H_2S to the required quantities for the methanol synthesis process (5 mol% CO_2 and 0.1 ppm H_2S) [22,26]. A 35 wt% concentration of monoethanolamine was used in the AGR system [22,26]. The syngas was next sent to the low-temperature shift unit (LTS) to raise the H_2/CO ratio [22]. The reaction was conducted over Ce-Ni-based catalysts [27]. The syngas was then fed to the reactor at 275 ℃ and 1 bar with a steam/CO mole ratio of 1 [24,27]. The LTS increased H_2/CO in the syngas from 1.6 to 2.54. Finally, once the syngas had been purified, it was fed to the methanol synthesis unit.

2.4. Methanol synthesis

Methanol synthesis is a critical step in converting MSW to gasoline, and it is described in more detail by Tijm et al. [28]. The clean syngas was converted to methanol using a copper/zinc oxide catalyst in a fixed-bed reactor with the following reactions [28].

$$CO + 2H_2 \leftrightarrow CH_3OH \qquad \Delta H = -90.7\ \mathrm{kJ/mol} \tag{1}$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \quad \Delta H = -40.9\ \mathrm{kJ/mol} \tag{2}$$

The conditions of the reactions were 300 °C and 50 bar with an H_2/CO ratio of 2.54 and a CO_2 concentration of 5 mol% [28]. The fresh syngas was fed to the reactor with the recycle stream. Unconverted syngas was separated from the product and recycled to the reactor until 95% of CO_2, CO, and H_2 were converted [29]. After removing the dissolved gases using a stabilizing column, the products of the reaction contained 95% methanol, 2% CO_2, and 3% water. The products were sent to the methanol-to-gasoline unit [22,26].

2.5. Methanol to gasoline (MTG) and gasoline separation

Methanol was converted to gasoline over a ZSM-5 zeolite catalyst in a sequence of four fluidized bed reactors [30]. The methanol was fed to the reactor at 330 °C and 14.5 bars. The reactor products, containing 44 wt% hydrocarbon and 56 wt% water, were condensed and then separated. The separation process of MTG products is the same as the process for separating crude oil. The hydrocarbon contained 82 wt% gasoline, 10 wt% liquefied petroleum gas (LPG), and 8 wt% fuel gas [30]. First, the water was separated from the gasoline using a separator. Then, the de-ethanizer column was used to separate the light hydrocarbons from the gasoline. The bottom effluent of the de-ethanizer column was fed to the stabilizer column to separate LPG from the gasoline [22]. The LPG contained 29 mol% propane, 4 mol% propane, 43 mol% i-butane, and 24 mol% n-butane [22]. The gasoline contained 52 wt% paraffin, 11 wt% olefins, 7 wt% cycloparaffins, and 30 wt% aromatics. The methanol-to-gasoline process is described in detail by Hannula [24]. The process is still at laboratory scale and needs further research and improvement to be commercialized and become well established.

2.6. Steam cycle and power generation

Heat as steam, which was used for the gasifier, gas purification, and electricity was produced from the steam cycle. The steam cycle was integrated with preheaters, steam generators, and superheaters to produce steam. The power was generated by a steam turbine and fuel gas combustion. The electricity produced can be utilized for various applications, such as pretreatment and gas purification. Unreformed syngas and tail gas were combusted in the power generation unit to achieve a plant that is energy self-sufficient, even though this has a negative impact on the overall yield of the plant.

3. Process simulation in Aspen Plus

The Aspen Plus software was used to simulate gasoline production via the SGMG process, and the simulation was used to calculate the mass and energy balance of the process. The steam gasification of MSW was simulated in Aspen Plus using a yield reactor [21]. Municipal solid waste and char were not available in the Aspen Plus data bank, so they were treated as non-conventional components. Table 1 presents the ultimate analysis of MSW and char on a dry basis to add MSW and char to Aspen Plus [31]. Experimental data were used for selectivity and conversions for methanol synthesis and the MTG process [30]. REQUIL in Aspen Plus was used to simulate the methanol synthesis reactions [22]. The MTG reaction was simulated in Aspen Plus using a reactor yield. In this study, kinetic expressions were not used since adequate data to develop the kinetic expressions were unavailable. The remaining unit processes were simulated as modeled in previously published studies [22,24,26].

Table 1. The ultimate analysis for MSW and char.

Ultimate Analysis	(dry basis) MSW (wt%) [31]	char (wt%)*
C	51.8	49.2
H	5.6	2.8
O	27.9	2.6
S	0.5	0.8
N	1.7	5.3
Ash	12.5	39.2

* It is calculated as the difference between MSW (feed) and syngas (product).

4. Capital and operating costs estimation

The size of the processing equipment was estimated based on the material and energy balance. The equipment cost of the process was calculated using published cost estimates of similar equipment. The equipment cost, based on equipment size, was adjusted using the rule of six-tenths. The estimation of capital and operating costs in this study are stated in US dollars (USD) at their 2020 value, using the Chemical Engineering Plant Cost Index (CEPCI) to update the costs to the 2020 USD. The total capital investment required to produce gasoline from MSW was estimated using the model costing technique. The *n*th plant assumption was the basis of the capital cost calculation. Table 2 presents the economic assumptions used to estimate MSP and the profitability of this project.

Table 2. The economic Assumptions.

Parameters	Value
Plant size	2000 DMT per day
Annual interest rate	10%
Macrs depreciation	7 years
Taxation rate	40%
Stream factor	90%
Cost of land	3% of Purchased equipment cost
Salvage value	10% of the Capital cost
Project life	20 years
Construction period	2 years
Working capital	5% of Total capital investment

5. Results and discussion

5.1. Mass and energy balances

The mass and energy flow of the gasoline production process was estimated using the Aspen Plus model. The steam gasification of MSW resulted in the formation of syngas and char; yields of these products were 68.1 wt%, 31.9 wt%, respectively. The syngas produced in the gasifier in this study was raw, but after purification, it was clean gas. Figure 2 illustrates the gas composition of the raw and clean syngas. As shown in Figure 2, the steam reforming and the gas purification processes increased the H_2/CO mole ratio from 1.6 to 2.54, which enhanced methanol synthesis. If the H_2/CO ratio is less than 2, which is the stoichiometric ratio, methanol production will decreased [29].

In the Aspen Plus simulation, 2000 DMT per day of MSW was fed to the SGMG process, producing 191 MT of gasoline per day, which represents a mass yield of 9.5%. The gasoline yield was 34.8 gallons per DMT of MSW, and the carbon efficiency of the gasoline product was 16%. Philips et al. [22] reported that the gasoline production yield from biomass, using the same process, was 66 gallons per DMT of biomass, and the carbon efficiency was 26%; these findings are higher than the results for this study owing to the feedstock properties. Ilkka Hannula [24] used the same process to produce gasoline from biomass; he reported that the gasoline yield was 71 gallons per DMT of biomass, and the carbon efficiency of the gasoline produced was 29% [24]. Swanson et al. [32] used Aspen Plus to simulate production of fuel from gasification of biomass, using Fischer-Tropsch technology instead of methanol synthesis and methanol-to-gasoline pathways. They found the gasoline yield was 61 gallons per DMT of biomass, which is similar to the yield when using methanol synthesis and methanol-to-gasoline pathways [32]. From these results, it can be concluded that using biomass as feedstock to produce gasoline via the SGMG process results in higher gasoline yield and carbon efficiency than using MSW as feedstock since the biomass has lower ash content.

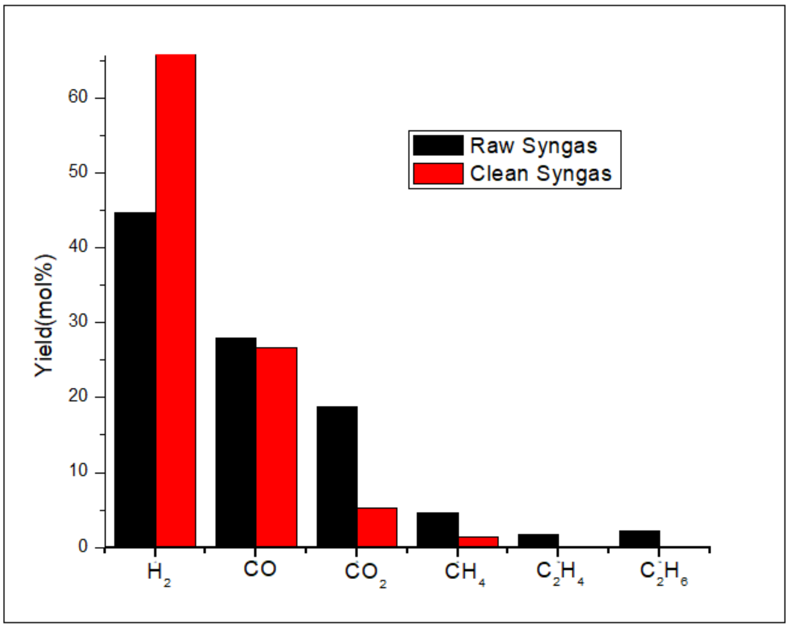

Figure 2. The gas compositions of steam gasification of MSW.

The energy efficiency of the process was quantified by comparing the energy input and output of the process. In this model, 2000 DMT per day of MSW produces 295 MW based on the lower heating value (LHV) of MSW, which is 13.4 MJ/kg [31,33]. The energy yield of this process is 32%, which is lower than the energy yield for producing gasoline from biomass using the same process, reported by Phillips et al. as 42% [22] and by Ilkka Hannula as 51% [24]. Swanson et al. [32] reported that the energy yield of gasoline production via gasification of biomass using the Fischer-Tropsch process was 49%. Even though the pathways for producing gasoline vary, the energy yield of each process is in the same range of 42 ± 10%. Figure 3 illustrates the total energy distribution of dry MSW, showing gasoline and LPG, as final products, recovered 32% and 5% of the LHV, respectively. Air-cooled exchangers consumed around one-third of the energy. In the power generation unit, fuel gas from the char combustor combined with the combustion of unreformed syngas, tail gas and light hydrocarbons produced power of 71 MW, which provides the required power for various units of the process shown in Figure 4. Reforming and gas purification required more than half of the plant's power since the compression of gases consumed a large amount of energy. The feedstock pretreatment and gasification consumed 33% of the plant power. The power production on-site met the power demand for the process, and no excess energy was purchased from the grid.

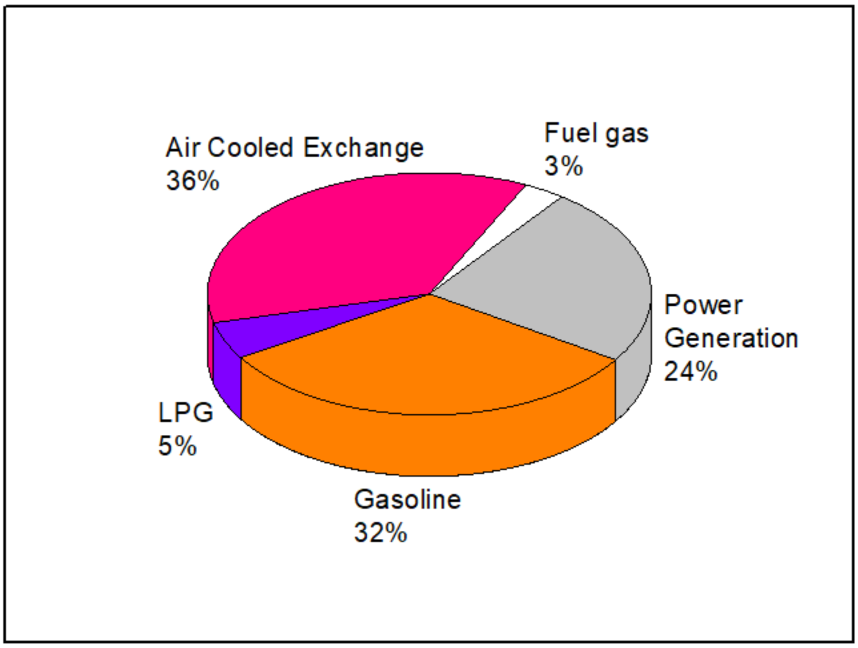

Figure 3. The overall energy analysis of dry MSW (LHV basis).

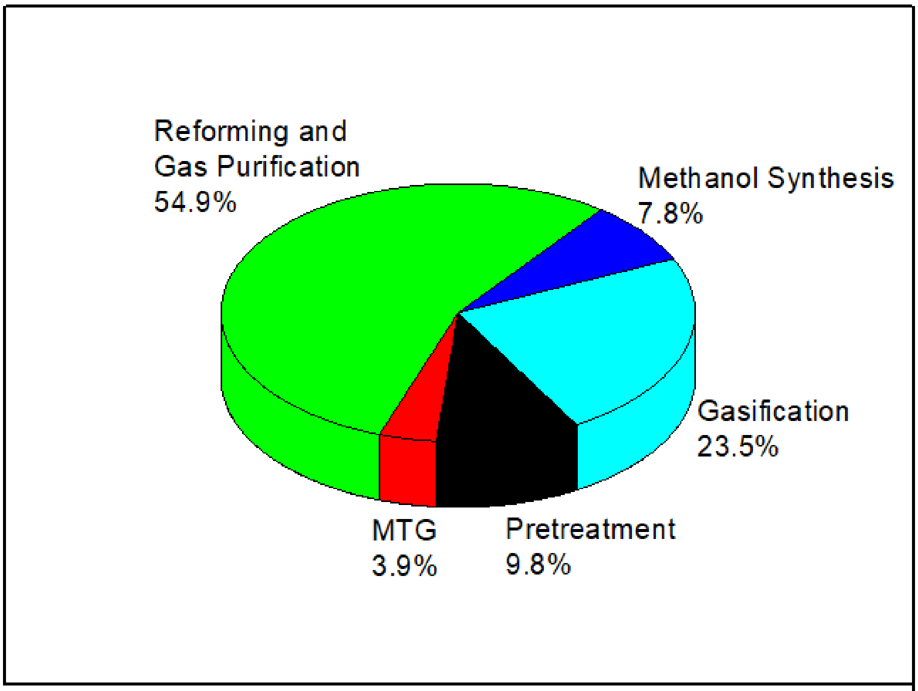

Figure 4. The plant power requirements.

5.2. Economic analysis

The total capital costs of gasoline production from MSW are shown in Table 3. The estimated total installed equipment (TIE) cost is $147 million, and the total capital investment (TCI) is $268 million. The plant's capital investment is strongly affected by the capital cost of pretreatment, the process steam cycle, and gas purification processes. The TCI of this process is less than the TCI for producing gasoline from biomass by steam gasification and Fischer-Tropsch technology, which Swanson et al. reported as $606 million for the same plant capacity [32]. Production of gasoline from MSW via the SGMG process was at lab-scale development, which means the total capital investment required is expected to decrease over time [22]. The estimated annual operating cost of gasoline production via this process was $56 million, as shown in Table 4. The cost of the feedstock was assumed to be free since MSW is garbage. Waste treatment costs were attributed to ash disposal and water treatment.

Table 3. The total capital investment.

Process	Value $MM	Contribution [%]
Pretreatment	28.7	19.6
Gasification	17.1	11.7
Gas purification	26.4	18.0
Methanol synthesis	19.1	13.0
Steam cycle and power generation	26.4	18.0
Cooling and utilities	4.2	2.9
MTG process	24.6	16.8
Total installed equipment (TIE)	146.5	100.0
Land (3% of TIE)	4.4	
Site development (5% of TIE)	7.3	
Indirect cost and project Contingency (66% of TIE)	96.7	
Fixed capital (FCI)	255.0	
Working capital (5% of FCI)	12.7	
Total capital investment (TCI)	267.7	

Table 4. The annual expenses.

Annual Expenses	Value $MM
Raw materials/olivine	6
Catalysts	4
Utilities	2
Waste treatment	5
Operating labor	4
Insurance and tax	5
Maintenance and overheads	8
Distribution and selling	5
The total cost of manufacturing	39
Capital depreciation	7
Average income tax	4
Average ROI	6
The total cost of production	56

Processing 2,000 DMT of MSW per day using the process in this study produced 23 million gallons of gasoline per year. The MSP of gasoline was calculated at $ 2.40/gal. The contribution of each cost component to the MSP shown in Table 5. The highest contributor to the MSP was maintenance and overheads. Phillips et al. [22] found that the gasoline produced from biomass using the same process was $1.95/gal owing to the high cost of feedstock. By contrast, Ilkka Hannula [24] reported that the MSP of gasoline production from biomass by the same process was $7.35/gal. The higher cost may be because this study was based on the European market. In this study, the feedstock was assumed to be free, which contributes to the lower price of the gasoline produced, even though the gasoline yield was low. The MSP for gasoline produced by steam gasification and Fischer-Tropsch pathways is in the range of $4–5/gal, as reported by Swanson et al. [32]. From the results of this study and Philips et al. [22], it can be concluded that producing gasoline from biomass or MSW via the SGMG process has more commercial potential than the Fischer-Tropsch pathway. Previous studies for producing gasoline from biomass using gasification showed that the MSP varied from $1.95 to $7.35/gal [22,24,34,35]. Larson et al. [34] conducted a techno-economic assessment for producing gasoline from switchgrass using gasification in a plant that was assumed to process 5000 DMT of switchgrass and found the total capital investment was $ 541 million, and the MSP of gasoline was 2.04/gal [34]. The MSP in that study is lower than the MSP of this study since the plant capacity for their study was higher, as was the yield of gasoline. Ramirez et al. [35] also performed a techno-economic analysis to produce gasoline from sugarcane bagasse using a gasification process with a plant capacity that was assumed to be 230 DMT per day [35]. They found the capital investment was $68 million, and the annual operation cost was $12.35 million [35]. Their results showed the MSP was $7.28/gal., which is higher than the MSP for this study. The MSP varied, depending on the plant capacity and the feedstock cost. From these results, it can be concluded that the economic assumptions have a significant impact on the MSP of gasoline. Thus, sensitivity analyses are essential to determine the effect of economic assumptions on the MSP.

Table 5. The minimum selling price (MSP) breakdown.

Expenses	$/gal	Contribution [%]
Raw Materials/Olivine	0.25	10.6
Catalyst	0.16	6.8
Maintenance and overheads	0.35	14.5
Utilities	0.09	3.6
Distribution & selling	0.22	9.0
Operating labor	0.17	7.2
Waste treatment	0.22	9.0
Insurance and tax	0.23	9.6
Capital depreciation	0.30	12.6
Average income tax	0.17	7.0
Average ROI	0.24	10.1
MSP	2.40	100

The sensitivity analyses were performed by varying one variable at a time, and holding all other variables at the base values, as shown in Figure 5. The sensitivity was estimated for a ±30% change in the rates of all variables except for plant capacity and feedstock cost. The sensitivity results illustrate that MSW cost and gasoline yield have the most significant impacts on the MSP of the gasoline produced. The estimate of MSW was set at $0 per DMT on the assumption that plant owners would not receive any fees for waste disposal from local authorities. If the owners received $25 per DMT as waste disposal fees, the cost of MSW would have a negative value (−$25 per DMT), which reduced the MSP of gasoline to $1.55/gal. By contrast, if the owners were required to pay $25 per DMT of MSW, the MSP would increase to $3.28/gal. Philips et al. [22] found that changes in the cost of feedstock had the same effect on the MSP. They reported that as the price of feedstock increased from $56/DMT to $92/DMT, the MSP increased from $1.95/gal to $2.50/gal. In the same way, as the feedstock cost decreased to $22/DMT, the MSP decreased to $1.44/gal [22]. Swanson et al. [32] maintain that the cost of feedstock had the highest impact on the MSP of gasoline produced from gasification of biomass using the Fischer-Tropsch process; when feedstock costs increased by 33%, the MSP of the gasoline increased by 11%. If the value of feedstock decreased by 33%, the MSP decreased by 10% [32]. Therefore, it can be concluded that the cost of feedstock has an impact on the MSP, which explains why the MSP in this study is lower than the values reported in existing literature [22,32].

Increasing the gasoline yield to 0.125 kg of gasoline/kg of MSW decreases the MSP of the gasoline to $1.86/gal. Decreasing the gasoline yield to 0.067 kg of gasoline/kg of MSW increases the MSP to $3.45/gal. Variability in plant capacity can also have a significant impact on the MSP. Increasing the plant capacity to 4000 DMT per day reduces the MSP to $1.88/gal, owing to decreases in production costs. Reducing the plant capacity to 1000 DMT per day increases the MSP to $2.83/gal, which supports the results of Philips et al. [22] who found that, as the plant capacity increased from 2000 DMT per day to 11,000 DMT per day, the MSP decreased from $1.95/gal to $1.21/gal. Decreasing the energy of the plant to 600 DMT per day increased the MSP to $3.90/gal [22]. Labor costs had a slight impact, increasing MSP to $2.47/gal if labor costs increased by $1 million per year, and decreasing the MSP to $2.33/gal if the labor costs were reduced by $1 million. Thus, capital investment and labor costs do not have a significant impact on the MSP of gasoline.

The ash content in the feedstock has a significant and direct impact on the MSP, as Figure 6 illustrates. The ash content of MSW varies from 3 wt% to 20 wt% [7], depending on the type of MSW. As the ash content increases, the MSP of the gasoline increases due to excess in production cost. Even for other processes, such as fast pyrolysis, the ash content has a significant impact on the MSP of the fuel produced. For instance, Almohamadi et al. [23] found that the MSP of fuel-producing from fast pyrolysis increased from $4.80 to $5.15/gal as the ash content in the biomass increased from 3 wt% to 5 wt% [23]. Increasing the ash in MSW leads to a decrease in the proportion of C and H in the feedstock by mass, which results in a decrease in gasoline yield and so increases the MSP. Furthermore, more make-up olivine is required as a catalyst when the amount of ash in the feedstock increases since some olivine is purged with the ash. Finally, the waste treatment cost increased with increased ash content.

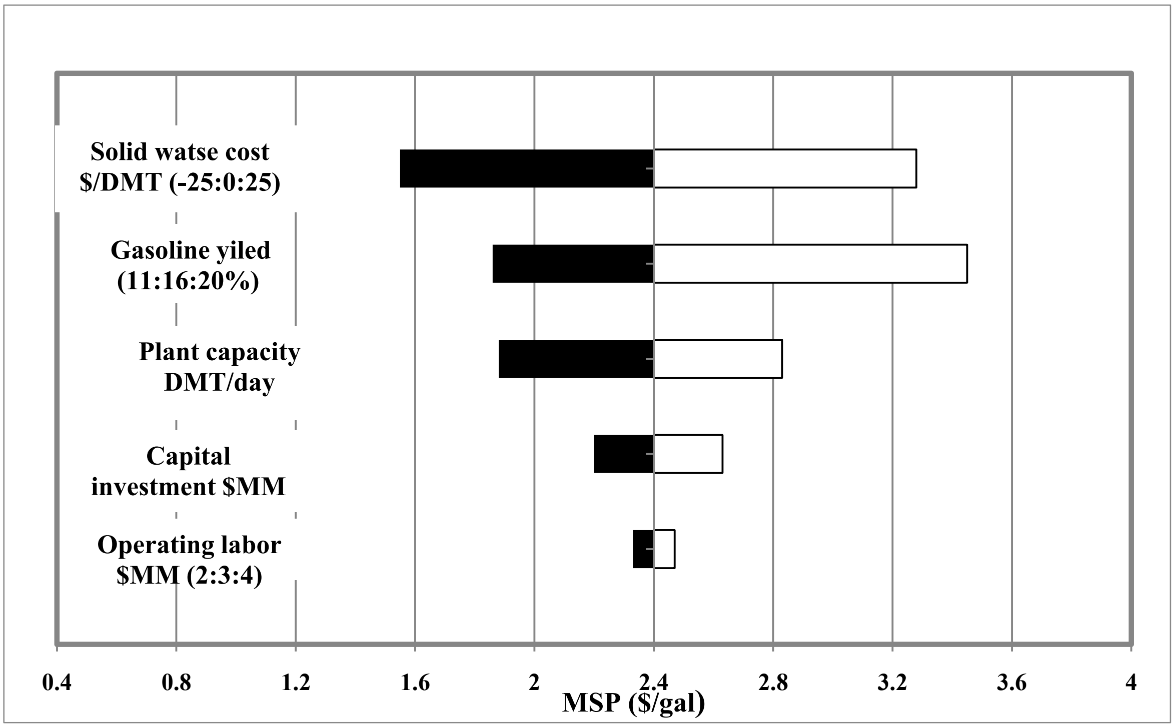

Figure 5. The economic sensitivities (±30% except feedstock and plant capacity).

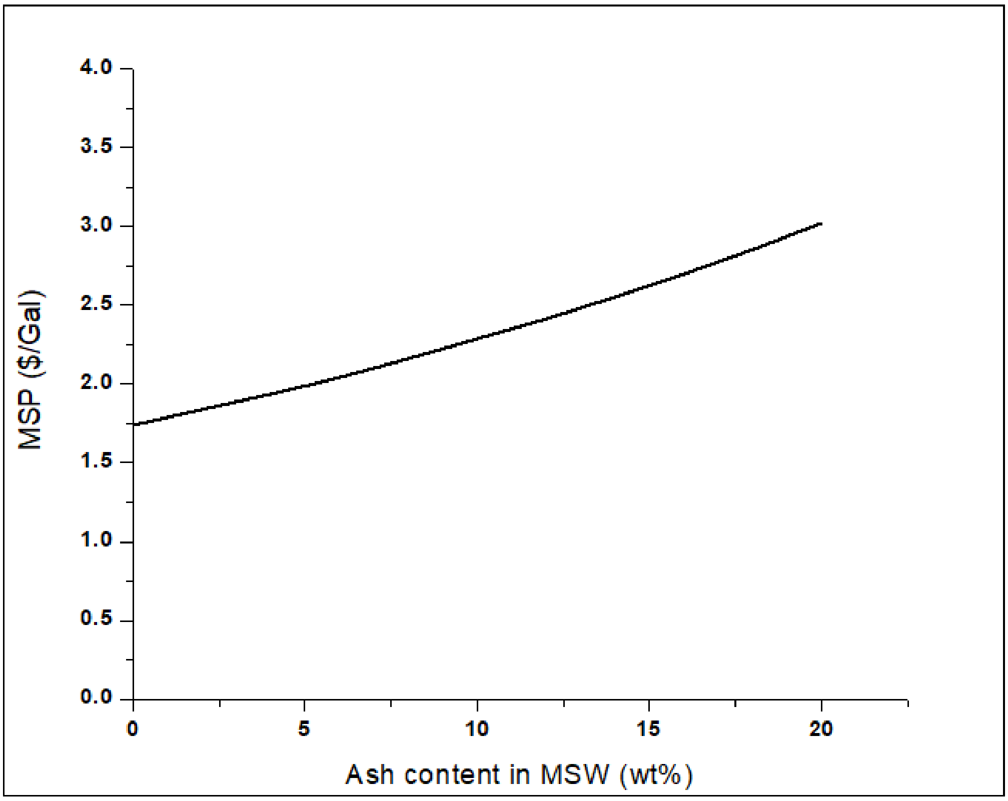

Figure 6. The effect of ash content in MSW on the MSP of gasoline.

Synthesis of methanol from MSW is already conducted on a commercial level, and a company called Enerkem [36] has built a plant to convert MSW to methanol in Edmonton, Alberta, Canada where MSW is converted to methanol by gasification combined with methanol synthesis [36]. The capacity of the plant is 100,000 metric tonnes of MSW per year, and the plant produces 10 million gallons of methanol per year [36]. Production of gasoline from MSW will reach the commercial stage following further research and development. The gasoline demand in KSA in 2015 was 7.6 billion gallons per year, 100% of which demand was covered by crude oil refineries [37]. According to Vision 2030, the KSA government plans to partially replace fossil fuels with renewable fuels. Table 6 shows that KSA produces around 15 million tons of MSW per year [38]. Using 66% of MSW as feedstock for the SGMG process would produce 348 million gallons of gasoline per year, which would cover 4.5% of the demand for gasoline in KSA. The results in Table 6 are based on data published in 2015. The average gasoline price in KSA in 2019 was $2.10/gal [39], which indicates excellent potential for gasoline production from MSW using a commercialized SGMG process in the future.

Table 6. Contribution of gasoline production from MSW to annual gasoline consumption in KSA.

	Value
MSW production in KSA (million tons/year) [7]	15
MSW used as feedstock for SGMG process (million tons/year)	10
Gasoline consumed per year in KSA (billion gallons/year) [37]	7.6
Gasoline yield (gal/ton of MSW)	34.8
Gasoline production from MSW (million gallons/year)	348
Contribution gasoline produce from MSW to gasoline consumed per year (%)	4.5

6. Conclusions

This study used Aspen Plus software to model the process of producing gasoline from MSW in a plant that could process 2000 DMT of waste per day and estimated the MSP for gasoline produced from this process. The conversion process used steam gasification, gas purification, methanol synthesis, and a methanol-to-gasoline process. The gasoline yield from this process was estimated at 9.5% by mass and 32% by energy. This study found that gasoline was produced from *n*th-plant steam gasification of MSW, followed by methanol synthesis and a methanol-to-gasoline process. The methanol synthesis process is well established and has been commercialized for several years, but the fluidized bed MTG reactor needs further research and development to be commercialized. The plant's total capital investment is $268 million, and the cost of production is $56 million. The MSP for the gasoline produced by the SGMG process would be $2.40/gal for a 20-year project life. The analysis shows that ash content and feedstock cost have a significant impact on the MSP. As the ash content increased from 12.5 to 20 wt%, the MSP increased from $2.40 to $3.02. If the plant owners received disposal fees of $25 per DMT, the MSP decreased significantly from $2.40 to $1.55. Around 15 million tons of MSW was produced in KSA in 2015. If 10 million tons was treated using the SGMG process, 4.5% of the demand for gasoline in KSA could be covered by the gasoline produced from MSW.

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Conflicts of interest

The author declares no conflict of interest.

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