THERMOCHEMICAL CONVERSION OF MSW FOR ENERGY PRODUCTION USING PYROLYSIS, GASIFICATION OR COMBUSTION

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ABSTRACT

Municipal solid waste (MSW) increases every year due to the world's expanding population and consumption. Therefore, researchers have been investigating ways to treat this MSW effectively and efficiently. The most common treatment is thermochemical conversion. Through thermochemical conversion, the waste is heated and converted into energy. Thermochemical conversion methods include pyrolysis, gasification, and direct combustion. Through years of research, it is now clear that each of these methods is comprised of several advantages and disadvantages. This review encompasses the information of each thermochemical process and suggests which method is more appropriate for MSW treatment in the future. Due to consistency, versatility, efficiency, and eco-friendliness, gasification is recommended to be more suitable for energy conversion and low pollutants emission for MSW.

INTRODUCTION

As the world's population grows, consumption grows with it. As of 2018, the population is 7.6 billion. By 2050, the population will increase approximately 2 billion to 9.6 billion people. Increased municipal solid waste (MSW) accompanies increased consumption. MSW is trash from municipalities (households, businesses, and institutions). In the United States during 2014, 258 million tons of MSW were made [4]. The waste fills landfills at a faster rate than ever. Thus, researchers have been looking for a solution to the massive waste epidemic. However, waste disposal needs to utilize environmentally sound process. Otherwise, one problem would sprout from another. If waste was disposed improperly, excessive pollutants could emit. In addition, to capitalize on the massive waste, methods have been made to convert the waste into energy. MSW's conversion into energy creates a renewable energy that can rival the traditional fossil fuels. Several conversions processes exist. In this paper, we will focus on the thermochemical conversion processes. The thermochemical conversion processes include pyrolysis, gasification, and combustion. Thermochemical conversion processes utilize heat to convert biomass into energy. Biomass is organic material that comes from plants and animals [4]. Biomass comes in many forms, such as plastics, leather, wood, rubber, yard trimmings, food, or paper products [1]. A pie-chart of components in MSW is in the figure below. Some of these components, including yard trimmings, paper, wood, and food remains, are biomass. Biomass stores energy from the sun through photosynthesis. Thus, when the material is heated, energy is released. As displayed in the table below, the biomass components of MSW store different amount of energy. In this case, energy is represented as the high heating value (HHV). The HHV Direct combustion, gasification, and direct combustion are utilize for MSW/biomass thermochemical conversion.

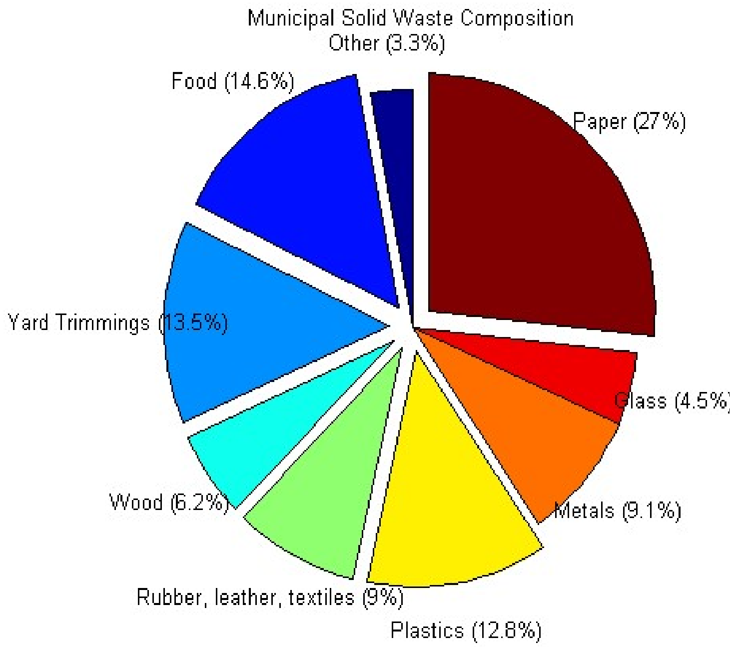

Figure 1: Municipal Solid Waste (MSW) Biomass Composition [4]

Material	High Heating Value (HHV)	
	MJ/kg	Btu/lb
Paper/cardboard	**15.8**	**6792.777301**
Food waste	**5.51**	**2368.873603**
Plastic	**32.56**	**13998.28031**
Textile	**17.24**	**7411.865865**
Rubber	**25.33**	**10889.93981**
Leather	**36.24**	**15580.39553**
Glass	**0.14**	**60.18916596**
Metal	**0.7**	**300.9458298**
Yard trimmings	**6.51**	**2798.796217**
Anthracite coal	32.6	14015.47722
Bituminous coal	30.3	13026.6552
Charcoal	29.6	12725.70937
Diesel	45.6	19604.4712
Gasoline	46.4	19948.40929
Biodiesel	40.5	17411.86587
Tar	36	15477.2141
Natural gas	52.2	22441.96045

Table 1: High Heating Values (HHV) of MSW Components (Highlighted) and Common Fuels [35][36][37]

METHODS

Through this literature, we reviewed the current thermochemical conversion of biomass and MSW. Articles were obtained using *ScienceDirect* from University of Maryland's Library Catalog, *Google Scholar*, and the *Academic Search Complete* Databases. Articles needed to be directly related to "MSW", "biomass thermochemical conversion", "pyrolysis", "gasification", or "biomass direct combustion". In total, 34 articles, 2 government websites, and two books were utilized.

Gasification

Gasification is the thermal conversion process that converts organic material to syngas. Organic material is decomposed in the presence of a gasifying agent containing oxygen, such as steam, CO2, O2, or air [1]. Syngas is gas mixture of carbon monoxide, hydrogen, methane, carbon dioxide, and some light and heavy hydrocarbons. These gases are incondensable at ambient temperature. Nitrogen, sulphidric, and chloridric (all pollutants) can be present in syngas as well, depending on the gasification process and operational conditions. Syngas can be utilized as is, or refined into another product. Bio-char is a product of gasification as well [13]. Char can be recylced into the beginning of the experiment again or be collected. Once char is collected, it has useful applications such as mixing with soil to enhance quality and nutrient content [36].

Gasification is a partial oxidation of the carbon in biomass/MSW. The oxidation provides energy for the rest of the process. In the case of gasification, the initial reactions are endothermic. Thus, there is a requirement for more energy. This energy is used to convert the feedstock into CO, CO2 and water [1]. These intermediates are then oxidized and react with the gasifying agent to produce syngas [1]. Syngas consists of H_2, CO, CO_2, H_2O, CH_4, C_2, C_3 [1]. Different gasifying agents are chosen based on reactants and apparatus of the experiment, thus leading to different results. For example, steam gasification increases H2 content in syngas, while CO2 gasification increases CO content [1]. Steam is the most commonly used is steam. With steam as the gasifying agent, the product gas has a high heating value (10-15 MJ/m3) as well. Oxygen is considered the best gasifying agent for power generation, since it minimizes tar production [5]. Carbon dioxide and air are other gasifying agents [5].

There are several types of gasifiers. The design relies on fuel availability, shape, size, moisture content, ash content, and final product applications. The two classifications for biomass/MSW gasifiers are fixed bed and fluidized bed. They are further classified based on their interaction with gasifying agents. The three types of fixed bed gasifiers are downdraft, updraft, and crossdraft. The two types of fluidized bed gasifiers are bubbling bed and circulating [5].

Compared to the other thermal conversion processes, gasification is the most effective and efficient. The heat capacity of gasification is higher than combustion and pyrolysis, due to gasification maximization of carbon and hydrogen available. Comparatively, pyrolysis and combustion rely more on secondary reactions. In addition, gasification has superior energy recovery rates [5]. Syngas amounts for 85% of the initial feedstock [30]. It also reduces MSW volume by 80 to 95% [30].

During an experiment by [5], researchers created models representing gasification, combustion, and pyrolysis to assess each's cost and efficiency. Gasification proved more efficient than the other two methods. Efficiences were found using the following equation on a lower heating value basis

$$\text{Net system efficiency}, \eta_{e,net} = E_{e,net}\, E_{th,del} + E_{th,aux}$$

where

$E_{e,net}$

net annual electricity output to the grid, GJ/yr;

$E_{th,conv}$

annual energy value of the conversion technology product, GJ/yr;

$E_{th,aux}$

annual energy value of the auxiliary diesel fuel if used, GJ/yr.

At a capacity of 20 MWe, Gasification sported a net system efficiency % [(energy in net electricity out)/(LHV of feed and auxiliary fuel) of about 31%, while pyrolysis and combustion only had efficiencies of 26% and 22%, respectively. Below is a table comparing the efficiency, product yield, and volume reduction to the other thermochemical conversion methods.

	Efficiency	Desired Product Yield	MSW Volume Reduction
Gasification	31%	85%	80-95%
Pyrolysis	26%	75%	65-75%
Combustion	22%	80-90%	90-95%

Table 1: Efficiency, Yield, and Volume Reduction Properties of Conversion Processes

Gasification requires feedstock to be dry. Biomass/MSW is considered dry once the internal temperature of the feedstock is 150 C°. The moisture content of feedstock must not exceed 25 wt% [13]. However, 10 wt% moisture is preferred. High moisture feedstock has low energy efficiency due to the moisture making the process more endothermic [1]. In an experiment done by [11], gasification was shown to reduce with decreased moisture weight percentage. In the experiment, biomasses with moisture content of 10, 15, and 20 wt% were tested. They were gasified between 650 and 900 C°. Due to the high moisture content, the biomass with 15 wt% and 20 wt% were unable to be gasified until about 680 and 720 C, respectively. Still, throughout the experiment, the higher moisture content biomass was more efficient. At the end of gasification (900 C°), biomasses with moisture content of 10, 15, and 20 wt% had efficiencies of 77.2, 76.8, and 76%, respectively.

Gasification occurs between 550 to 900 C° with air as the oxidizing agent, or 1000-1600 C° for other agents. Low pressures are preferred for the process. At low pressures, there is higher H2 and CO content, as opposed to methane which is produced at high pressures [1].

As shown in the figure below, biomass/MSW is first dried. Biomass/MSW is initially pre-dried then dried again once it enters the gasifier reactor. The moisture from the drying process becomes steam. Then, it enters into a phase of pyrolysis. In gasification, pyrolysis is the act of cracking chemical bonds to form new molecules with a lower molecular weight. The biomass/MSW is reduced. At this stage, char and some gases are produced. In the next stage, the intermediate is oxidized and lightly combusted. Volatile gases are oxidized. This stage is the most important in determining the quality of the gas. The gases syngas is produced and collected. The remains of the biomass/MSW are converted into biochar and ash. Tar, a liquid, is also produced. The proportion of each is based on temperature, pressure, and processing time [5]. Gasification is an efficient process.

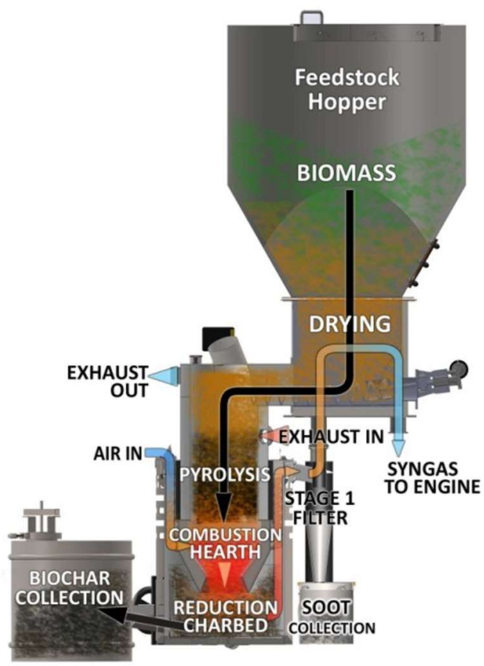

Figure 2: Gasification Process [17]

Syngas is the most versatile product out made by pyrolysis, combustion, and gasification. Its composition is not significantly changed based on the feed material, except for some. For example, the gasification of straw produces more hydrogen. Syngas can be upgraded to a biofuel, such as bioethanol or biodiesel, or synthesized to create methanol, ammonia, or value added chemicals. Value added chemicals include gasoline and diesel, among others. Syngas can also be used directly to generate electricity using a boiler. Syngas can also create power using turbine, engine, or fuel cell, but the gas must be refined first [13]. Engines are not yet compatible with syngas. Engines require high quality fuel. Due to the pollutants of syngas (tar, undesirable gases), it cannot be used [13]. Kilns and boilers can use syngas directly as well. This is due to tar and undesirable gases being burned in the process. Process heater deal with dirty gases stream relatively well also [23]. Syngas can be converted into transportation fuel (through Fischer-Tropsch synthesis), methanol, and ammonia [13]. Compared to other thermochemical conversion method products, syngas not only has more applications, but also more important applications. The table below shows the primary and secondary uses of each thermochemical conversion process.

	Product(s)	**Primary Uses**	**Secondary Uses**
Gasification	Syngas, Tar Char	Upgrading Electricity generation Synthesis	Transportation fuel Biofuel Value added chemicals Power generation Methonal and ammonia
Pyrolysis	Bio-oil char	Biofuel Chemical Refinement	Fetlizer Food Coloring Agrichemicals
Combustion	Ash, char, heat	Electricity & heat generation	None

Table 2: Products, Primary Uses, and Secondary Uses of Thermochemical Conversion Methods [13][30]

The downside of syngas is tar. Tar is a generic term for organic compounds present in syngas, excluding gaseous hydrocarbons. These primarily consist of mixed oxygenates, phenolic ethers, alkyl phenolics, heterocyclic ethers, and polyaromatic hydrocarbons [16]. The composition of each depends on feedstock type and gasification process [13]. Tar is problematic since it makes syngas undesirable, due to carcinogenic emissions. Tar can clog pipes and ruin potential fuel [1].

There are a few solutions so far in regard to tar. If syngas needs to be combusted, the tar can be combusted as well. Tar will even add calorific value. [16]. However, once syngas is cooled, tar condenses. Typically, tar will condense between 250-300 K. This is problematic in the conversion of syngas and fuel cell applications [16]. Modifying the operating conditions is a primary tar removal technique. Parameters, temperature profile, ER, type of gasifying agent, S/B, gasifying agent to biomass /MSWratio, and feed rate all impact the amount of tar that is created [16]. Introducing catalysts, such as dolomite, limestone, olivine, char, among others to the bed of gasifier reduces tar [16]. Wet scrubbing, liquid sprays into the gas stream, condenses tar compounds and simultaneously removes particulates. Still, these tar removal processes are costly. Once tar is removed, it can be converted to smaller gas products including H_2, CH_4, CO and CO_2 using catalytic conversion.

Pollutants and impurities from gasification include NH_3, HCN, nitrogen gases, H_2S, sulfur gases, HCl, alkali metals, organic hydrocarbons, and particulates. Cooling and gas scrubbing are used to remove these pollutants from syngas [23]. Compared to combustion of biomass/MSW, gasification is an environmentally cleaner process. When syngas is used in fuel cells and steam cycles, the gas has less influence on the environment than combustion [13]. Gasification does not emit any greenhouse gases either [16]. Tar condensed in water during gasification can negatively impact water environment as well if disposed improperly [6].

PYROLYSIS

Pyrolysis is the thermal decomposition of feedstock in the absence of any kind of oxidizing agent [1]. Therefore, oxidizing agents air, O_2, H_2O, and CO_2 are not present in the process. Pyrolysis, as related to MSW, is typically referred to as fast pyrolysis. This process is advanced and can be controlled to produce a high liquid yield of a product called bio-oil. Slow and catalytic pyrolysis are other forms of the conversion method [32].

Pyrolysis typically takes place in a reactor. The most common reactor used is the fluidized bed reactor. After pyrolysis, bio-char, gas, and liquid are produced. The level of each depends on several variables, including temperature, type of catalyst, and the type of feedstock (biomass/MSW). Heating rate, the rise in temperature per unit of time, and vapor residence time, the time during which oxygenate vapors formed during pyrolysis are removed or allowed to stay, also factor into pyrolysis. Vacuum pyrolysis and rotating cone pyrolysis are other types of reactors [1].

Prior to pyrolysis, biomass/MSW must be dried, due to the factor that the water present prior to the reaction is present in the final product. There can be no more than 10 wt% of water in the feedstock. Biomass/MSW must be ground into small particles as well [2]. This can be .02 to 2 mm, depending on the type of reactor used [7].

Pyrolysis can be done with wet biomass/MSW, but it takes a much longer time. In an experiment by the Institute for Thermal Power Engineering at Zhejiang University, multiple municipal waste samples were tested using pyrolysis. The samples included PVC plastic, PE plastic, vegetal waste, rubber, orange husk, and wood. During the experiment, it was shown that with higher moisture content, pyrolysis takes a much long time. During the experiment, most samples were decomposed and released gas in less than 7 mins. Undried vegetal waste and orange husk were the only two that did not. Instead, it took these two samples about 15 min to decompose and release gas. Vegetal material and orange husk were both high in moisture content, 86.86% and 73.93%, respectively. [8].

The process of pyrolysis can be shown in Figure 2. As shown, the feedstock is first dried and grinded. Then, it enters into the reactor without an oxidizing agent. The reactor must be heated in order for pyrolysis to take place. Heating creates a vapor. Then, the vapor goes through a cyclone. In the cyclone, leftover char is filtered out. Then, the vapor is cooled using water. The cooling process condenses the gas and produces bio-oil. Leftover gas is recycled and used in the beginning of the reaction again.

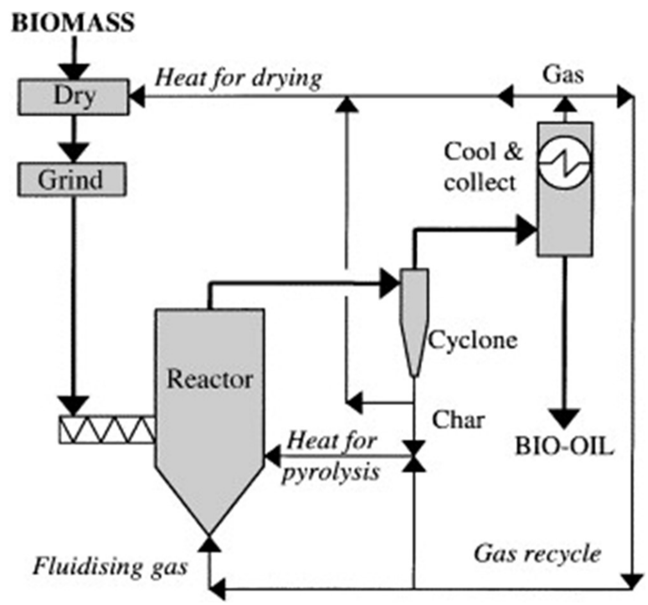

Figure 3: The process of pyrolysis for biomass/MSW [2]

Low temperatures and long residence times produces more solid products, specifically bio-char. High temperatures and long residence ties produce more gas products. This is due to a high amount of cracking. Cracking is the process of breaking down large hydrocarbon molecules into smaller parts, either at a high temperature and pressure, or utilizing a catalyst. Moderate temperatures and short residence times produce more bio-oil, the liquid yield [1].

The optimal temperature for pyrolysis is 500 C°. When the reactor temperature is 500 C°, bio-oil is moderately produced. Below 500 C°, too much bio-char is produced. On the other hand, above 500 C°, cracking increases, producing more gas. Moderate yields can be made between 450 and 550 C°. With a residence time of 1 s, yields of bio-oil maximize to about 75% [1]. Smaller but moderate yields can still be made with a residence time up to 5 s [2].

Through pyrolysis, biomass and solid wastes convert to the liquid product bio-oil (also referred to as pyrolysis oil). During the thermal experiment, a vapor is produced. That vapor is then condensed and becomes the fluid bio-oil. The liquid is dark brown and mobile. It is composed of water, pyrolytic lignin, and formic and acetic acid [27]. It has a high boiling point and melting point as well. Bio-oil is also acidic, with a pH of 2.5. Oxygen, carbon, and water mainly compose bio-oil (46-48, 44-47, and 20-30 wt% respectively), while hydrogen and nitrogen comprise a small amount (6-7 and 0-.0.2 wt% respectively) [2]. The bio-oil can be used directly as fuel in static applications, such as boilers, furnaces, engines, and turbines [7]. Furthermore, bio-oil can be refined into other products. These products include fertilizers, agrichemicals, or food flavorings. Pyrolysis can be converted into fuel for transportation, but it is not economically sound [6].

Once bio-oil is produced, there are some problems. Biomass/MSW needs to be dried prior to pyrolysis since water content present in the reactants will be present in the product as well. Considering MSW can have high water content, using pyrolysis for waste treatment could be problematic. In addition, bio-oil also has high oxygenate content. Due to the oxygenate content and water, bio-oil's energy density is only 50% of petroleum, which is poor. The oxygenate portion cannot be from removed through heating methods, since heating methods, like distillation, will cause solid residue to form. The bio-oil produced through pyrolysis is unstable as well. Over time, viscosity, the resistance to flow, and phase separation increase. Pyrolysis is insoluble in hydrocarbon solvents as well. However, if stable solvents, such as methanol or acetone, are introduced to biofuel, instability and viscosity decrease [1].

Since bio-oil is liquid product, it is easily transported and handled. In addition, the fluid does significantly damage the environment. In research done by [3], researchers used respirometery to assess the biodegradability of bio-oil. They concluded that in the presence of oxygen, bio-oil degrades much faster than diesel fuel. In addition, during a study done by [29], bio-oil was converted into fertilizer by combining it with nitrogen (ammonia). The fertilizer was then tested on soil. During the experiment, the fertilizer did not damage soil microorganisms. Thus, bio-oil (in its modified state at least), does not change the carbon amount in soil. Another environmental upside of pyrolysis is that the production of pollutants can be controlled. Thus, gas scrubbing, an air pollution removal technique, is not required. This is important since gas scrubbing can be expensive [8].

However, small amounts of chloride, nitrogen, and sulfur are released during pyrolysis [30]. Bio-oil can be potentially hazardous to humans however. It has potential for dermal toxicity, eye irritation, and inhalation toxicity. Pyrolysis produces low emissions of PAHs, methane, ethlylene, and di-PCBS. In addition, high emissions of NO, NH3, and HCN are produced as well.

DIRECT COMBUSTION

Combustion is the thermal oxidation of hydrocarbon material feedstock that includes MSW and biomass. It is a rapid reaction of MSW/biomass and oxygen to produce thermal energy and flue gases consisting of CO2 and water plus trace pollutants including particulate matter and smoke [23]. It is currently the main technology route for bioenergy processing. It is responsible for 90% of the world’s bioenergy [21]. Through combustion, biomass in MSW is heated directly to the point of combustion. Hot volatile gases are released. These hot gases can be used for heating in small or large combustion units, source of process heat, or water heating in boilers, electricity units, or larger heating system [21].

The process of combustion is simple. There are three phases: drying, releasing volatiles, and char conversion. In the first phase, the feedstock needs to be dried. Biomass/MSW needs to possess a moisture content percentage of 10-20 wt%. Thereafter, biomass enters a combustor. Under the pressure of heat and great energy, the feedstock is converted into volatile gases and biochar. Volatile gases include CO, CO2, H2O, methane, and other hydrocarbons [18]. Then, the gases mix with and burn with flame. The char then burns and turns to ash. This process provides heat along with CO2, H2O, and smoke [24]. The figure below provides further clarification. For combustion to take place, the feedstock must be heated between 850 and 1200 C° [30].

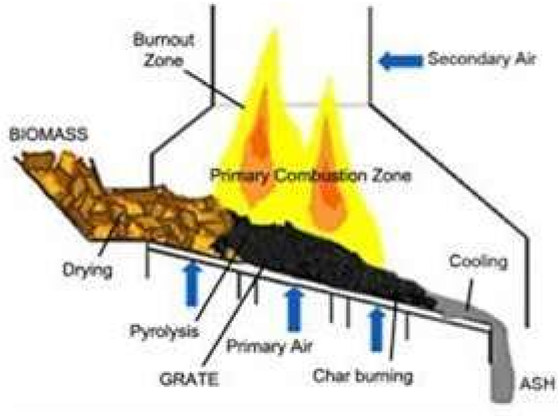

Figure 4: The process of combustion, with a fluidized bed combustor [31]

Combustion takes less time than the other processes. Combustion also reduces the volume of feedstock by 90-95% [19]. It could prove useful in removing waste alone.

MSW/Biomass combustion is done through a combustor. The design of combustor depends on energy and heat capacity and performance. [21]. There are a variety of combustors, ranging from massive controlled furnaces used in industry to traditional household stoves. Combustors are grouped into two categories: small-scale and large-scale systems. Small scale systems are generally used for small-scale heating and cooking. Large-scale systems are utilized for power and heat generation in industry. [23].

The disadvantages of combustion include agglomeration, ash fouling, and insufficient supplies for bulky biomass/MSW to adapt with modern electric power plants [23]. The common problems associated with burning fuel are present in biomass/MSW combustion. Compared to the other thermochemical conversion processes, combustion is not too efficient. In addition, pollutants are released during the process. Pollutants from combustion include dioxins, CO, NO, TOC, among others. In an experiment done Lodz University of Technology in Poland, various biomasses/wastes were combusted and compared for their emissions. They tested coal as well. In the results, coal had a lower total CO emission than the other biomasses/wastes combusted. As for NO and TOC, the emissions are for biomass and coal are similar or slightly worse. Thus, it is improper to say that biomass burning is environmentally friendly [15]. Ultimately, combustion is a poor process, especially compared to its competitors. MSW volume reduction and feasibility do not redeem the pollutants and inefficiency of the process.

COST-BENEFIT COMPARISON

A cost-benefit analysis study was done by [19]. In the study, cost-benefit analysis was done on wood chips to discover the cost benefit of disposing municipal waste through gasification. The experiment also utilized combustion, so there would be a comparison to the current popular method. In the study, an internal rate of return (IRR) and a net present value (NPV) were calculated. The IRR is the rate at which a project breaks even [34]. serves to prove how often a return on investment is achieved for a process. It was found using an algorithm in Matlab. The NPV is the present value of cash flows at the required rate of return of a given project compared to the initial investment [33]. It serves to prove if a process is sustainable long term and worthwhile. It was found using the following equation

$$\mathrm{NPV} = \sum_{t}^{LT} \frac{C_{it}}{(1+r)^t} - C_0$$

Where LT is the lifetime of a facility (20 years), r is the discount rate, C0 is the total initial investment, and Ct is the net cash inflow during the year t.

In the analysis, gasification scored a positive mean in IRR and NPV (.19 and 7.95×10^8 US$, respectively). A positive average means that, more likely than not, gasification is economically viable and will make a return on its investment.

The same cost benefit analysis proved combustion is not financially viable. Combustion scored negative mean values for both the IRR and NPV (-1.63 and -4.48×10^9 US$, respectively). Not only were the scores negative, but they were negative compared to those calculated for gasification. That means that combustion is unlikely to be economically sustainable or return value on its initial investment, especially compared to gasification.

During [5] models were created for atmospheric gasification, direct combustion, and pyrolysis to compare costs and efficiencies. Total plant costs took into account feed pretreatment, major equipment costs (piping, electrical, civils, structures), commissioning, contingency, contractors' fees, and interest during commission of each process. Each model processed wood biomass with a moisture content of 7 wt%.

. In the models created by [5], gasification was the most expensive method, followed by pyrolysis, and then combustion. In terms of total plant cost, the models predicted the total plant cost of combustion, pyrolysis, and gasification to be $2,553.89, $3,234.25/kWe, and $4,312.34/kWe, respectively, at 20 MWe net system capacity. Capital costs for gasification are higher than pyrolysis, due to land usage. Product transportation is cheapest for pyrolysis, since bio-oil is a liquid.

CONCLUSION

Gasification is the ideal MSW thermochemical treatment method. While pyrolysis and combustion are decent methods, gasification is far superior. Gasification should be used for biomass thermochemical treatment with MSW.

Syngas has several energy uses, including direct uses. It can be converted into valuable secondary products, including transportation fuel, such as biodiesel. Furthermore, syngas can be refined into value added chemicals, like gasoline. The opportunity to turn MSW into transportation fuel to replace traditional fossil fuels is too valuable. Meanwhile, direct combustion and pyrolysis' products cannot be used for transportation energy at all. To create a renewable energy source that can rival fossil fuels, the energy source must be applicable to several industries and uses. With the ability to be used as fuel or produce electricity and heat using variety of different machines, syngas definitely has this quality.

For the most part, syngas is not impacted by the type of feedstock used. Therefore, no matter the MSW distribution, a consistent product will be made. This allows manufacturers to properly plan the secondary products as well. Gasification is stable process. The same cannot be said for pyrolysis or combustion. There is too much variance associated with their products.

Tar production in syngas should be overlooked. If syngas is combusted, tar does not need to be removed. For tar-less syngas applications, tar removal processes are already being developed, including wet scrubbing and catalyst addition. System parameter modifications can minimize tar production as well.

For municipal waste treatment, gasification effectively reduces waste volume. As previously stated, through gasification, MSW volume is reduced by 80-95%. Therefore, gasification's worst possible outcome will still deplete 80% of MSW, thus clearly most of the land used for a landfill. In addition, during gasification, 85% of feedstock recovers as the product (syngas). Even though the process is expensive, the product volume is great. Gasification's cost decreases as the capacity increases as well.

Gasification is an improvement environmentally compared to current popular energy methods. Gasification does not emit greenhouse gases and only a limited amount of nitrogen, chloride, and sulfur. Meanwhile, approximately 6,500 million metric tons are emitted in the US, mainly through fossil fuels. At the same time, direct combustion emits a problematic, large amount of pollutants. With the amount of MSW there is, direct combustion would emit so many pollutants that the world's environment would be impacted. Pyrolysis emits those same pollutants as well; but in its case, those pollutants could end up in public waters. Through MSW gasification, land and environments covered in trash and litter will have the opportunity to improve and become healthy again as well.

Taking all of this into account, gasification is the ideal MSW treatment method. Despite the higher costs, the versatility of syngas is more valuable than the other processes' products. Furthermore, according to the model in [19], syngas' high cost is likely to be worth it. The process justifies its investment and is economically viable.

SUMMARY

In conclusion, thermochemical conversion provides MSW treatment with a bright future. Biomass, organic material containing energy from the sun, is a great solution to decreasing fossil fuels. The organic matter is a renewable energy, since organic material and waste will always be created. Thermochemical conversion is an efficient method to maximize the potential of the world's large waste problem. With thermochemical conversion, landfills will decrease environmentally soundly, rendering a healthier planet.

Gasification sets itself apart from the other conversion methods, due to its product versatility, consistency, economic viability, and process efficiency. The product syngas can also be transformed to gasoline, biofuel, and diesel. Furthermore, syngas can be used in gas turbines, engines, boilers, and fuel cells. Since the process is consistent, secondary products can be properly planned for. The process has disadvantages of tar production, high cost, and trace pollutants formation and emission; it is still the best solution to MSW treatment due to its superior efficiency.

Gasification still requires further research, developments and innovations. While gasification is economically viable, the process is still expensive. Cheapening the process will increase profits and efficiency. Synthesizing a new tar removal treatment would be effective. Currently, wet scrubbing is expensive. Utilizing a new tar removal method or improving current ones would be extremely helpful for gasification in the future.

The MSW problem in the world is a problem that will only become bigger. A solution needs to be met. There is still a fair amount research to be done in gasification. In its current state, gasification is not good enough to implement in large scale treatment. Therefore, a greater emphasis needs to be placed on biomass conversion research and MSW treatment. With gasification as our biomass/MSW conversion technology, the world can become a healthier place, through decreased landfills and pollution from fossil fuels. MSW is potentially the renewable energy source we have all been looking for.

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