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Production of sustainable energy from solid waste by pyrolysis - a review

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ABSTRACT

Environmental pollution is the major problem of the modern society associated with rapid urbanization and industrialization. The thermal technologies such as pyrolysis have been developed for waste reduction and environmental protection. Pyrolysis processes are optimized for fuels (liquid, gases, and char) production by thermal degradation of solid waste, in the absence of air.
This study involved a brief review of waste pyrolysis potential. The pyrolysis as a thermal technology is used at commercial scale, predominately in Europe and Japan. The focus of this paper is on the types of pyrolysis technologies which include amounts and products type, reactor design, and economics. Advantages and disadvantages of pyrolysis are also discussed and compared with incineration as a very similar thermal process.

1. Introduction

The primary aim of the waste management system in developed countries is resource recovery from waste. Waste-to-energy technologies, such as thermal technology of pyrolysis, incineration, or gasification have been implemented for managing municipal solid waste in many countries all over the world for many decades. These thermal technologies are energy-intensive processes that attempt to reduce the volume of waste by converting it into fuel or energy. Most of the thermal technologies attempt to treat large quantities of heterogeneous mixed municipal solid waste (Tangri and Wilson, 2017).

One of the greatest challenges for future generations is understanding and sustainable managing with large quantities of waste, as an inevitable product of society. Each person consumes a certain different amount of products, and more important, produces a large amount of waste. The disposal of waste became a world huge problem. In our modern societies, the amount of waste generated by the average consumer constantly increases. It is estimated that the statistical inhabitant of Western Europe produces more than 450 kg of garbage per year, or each person produced 475 kg of municipal waste only in 2014 (Hauser and Blumenthal, 2016). *World Energy Council, waste-to-energy*, estimated that global waste generation will double to over 6 million tons of waste per day by 2025, and the rates are not expected to peak by the end of this century (World Energy Council, 2016). The treatment, management, and disposal of municipal solid waste (MSW) are common concerns in every country. Different system analysis tools (Finnveden and Moberg, 2005) are available at the present time, but the most commonly applied tool to analyze environmental burden for waste management technology, as well as a system, is life cycle assessment (LCA). According to this data, the waste management sector faces a problem that cannot be solved on its own. The Kyoto Protocol predicted a reduction of greenhouse gas emissions because the global warming situation would likely be increasing day by day. These concerns have boosted the importance of research for alternatives to petroleum fuel because the global energy supply is based on fossil fuels (oil, natural gas, coal), of which the reserves are finite (Albrecht, 2015).

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Waste is defined as an unusable or undesired product of society, but a valuable energy resource as well. Different waste treatment options are available now, there is not a single technology that can solve the waste management problem (Zaman, 2010). Different countries choose different strategies, depending on their social, economic, and environmental criteria. These decisions can help improve future energy security and environmental sustainability (Tehrani et al., 2009). The energy sector can be a perfect match for waste reduction because of its need to continuously meet growing energy demand. If waste-to-energy (WTE) technologies are developed and implemented, then a correct waste treatment strategy and an environment-friendly energy production can be achieved. Energy recovery from waste can solve two problems at the same time in the waste management and energy sectors. First, there is a reduction and treating of non-recyclable amounts of waste and second, generation high energy amount which can be included in the energy production in order to satisfy the consumers' needs (Chen et al., 2014).

The pyrolysis is considered to be an innovative alternative for treating municipal solid waste (MSW) that obtains different chemicals and fuels. Pyrolysis processes are better than conventional MSW incineration because energy can be produced in a cleaner way. Also, there are lower productions of nitrogen oxides (NO_x) and sulphur oxides (SO_2) and better quality of solid residues can be expected from this thermal technique for MSW (Saffarzadeh et al., 2006). The MSW pyrolysis is more flexible technology than conventional incineration and it's more interesting for small cities and towns. There is growing difficulty in finding new sites for incinerators and landfills in the cities, so the pyrolysis is the technology for long-distance transport prevention. All MSW treatment facilities, due to capital cost limitations that are unsatisfactory, ensure environmental safety, but the pyrolysis plants of proper capacity with energy products output could be a suitable alternative (Chen et al., 2014).

The focus of this paper is pyrolysis, a waste thermal technology, as a potential solution for municipal solid waste reduction. The primary aim of this paper is the identification of challenges, and potential solutions for municipal solid waste reduction and achieving greenhouse gas using thermal technologies. The MSW thermal processes discussed in this paper are thermochemical processes. Pyrolysis, as a highly effective way of waste recycling and disposal, is a thermal process of degradation of MSW that generates energy in the form of fuel.

2. Types and sources of waste as an energy resources

Waste is an inevitable product of society. The term solid waste is usually used to describe non-liquid materials arising from domestic, trade, commercial, agricultural, and industrial activities, and from public services (Sasikumar and Krishna, 2009). Figure 1 illustrates the composition of solid waste worldwide, but specific waste products deriving from construction, industrial, and commercial waste are not specified in this figure.

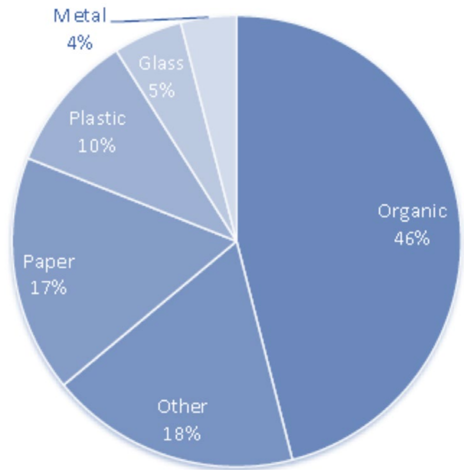

Figure 1. Composition of global MSW (Hoornweg et al., 2013)

The components that constitute MSW are mainly paper, textile yard waste (including fallen leaves and branches, etc.), food wastes, plastics, and a small amount of leather and rubber, metals, and glass. The most dangerous solid waste is the waste that does not degenerate or it needs a long time to degenerate. The time of degeneration of different types of solid waste are shown in Table 1 (Hoornweg et al., 2013).

Table 1. Approximate time for degeneration of some solid waste

Organic waste such as vegetable and fruit	**A week or two**
Paper	10 - 30 days
Cotton cloth	2 - 5 months
Wood	10 - 15 years
Woolen items	1 year
Tin, aluminum and other metal items such as cans	100 - 500 years
Plastic bags	Million years
Glass bottles	Indefinite

MSW from residential, industrial, and commercial sources is the most common waste stream used for energy recovery. The composition of different types of available waste is very important when waste is used as an energy resource. The calorific value of the waste, or the energy content, is a key factor which determines a possible extracted energy. Table 2 shows approximate net calorific values for common fractions of MSW (Auckland Council, 2011).

Table 2. Calorific values of selected fuels and fractions of MSW

Fuels	Q, MJ/kg	Fraction of waste	Q, MJ/kg
Natural gas	36 - 50	Paper	16
Diesel	46	Organic material	46
Black coal, various types	29 - 32.7	Plastic	36
Lignite briquettes	21	Glass	0
RDF fuel	13 - 23	Metal	0
Wood	15	Textile	19
Crude lignite	10	Other materials	11
Residual waste, unsorted, (Austria)	8 - 12	Residual waste, unsorted (China)	3.5 - 5

3. Modern methods of processing municipal solid waste

The choice of WTE technology will be largely dependent on the nature and volume of the incoming waste stream. Waste is now treated as a resource, not as the valueless garbage. Resource recovery is one of the prime objectives in a sustainable waste management system. There are different methods and generally accepted classification of technologies for the treatment of MSW. Some pathways of MSW processing are depicted in Figure 2.

Highly wet food wastes should be processed by biochemical/biological treatment. The MSW fractions such as plastics, paper, cloth, wood, and yard wastes should be processed using thermal technology (Chen et al., 2014).

4. Advanced Thermal Treatment - Pyrolysis

There are differences between Advanced Thermal Treatment and traditional Incineration technologies. Pyrolysis, in contrast to combustion, is the process of thermal degradation of a substance in the absence of oxygen that produces recyclable products, including char, oil/wax, and combustible gases (Figure 3). This process is endothermic and requires about 1 to 1.5 GJ of thermal energy per ton dried MSW (Zaman, 2010). An external heat source is essential to maintain the temperature, usually between 300 °C to 850 °C in the reactor.

The aim of using thermal methods, such as pyrolysis in the waste management sector is a reduction of MSW volume, the conversion of waste into harmless materials, and the utilization of waste hidden energy as fuel, heat,

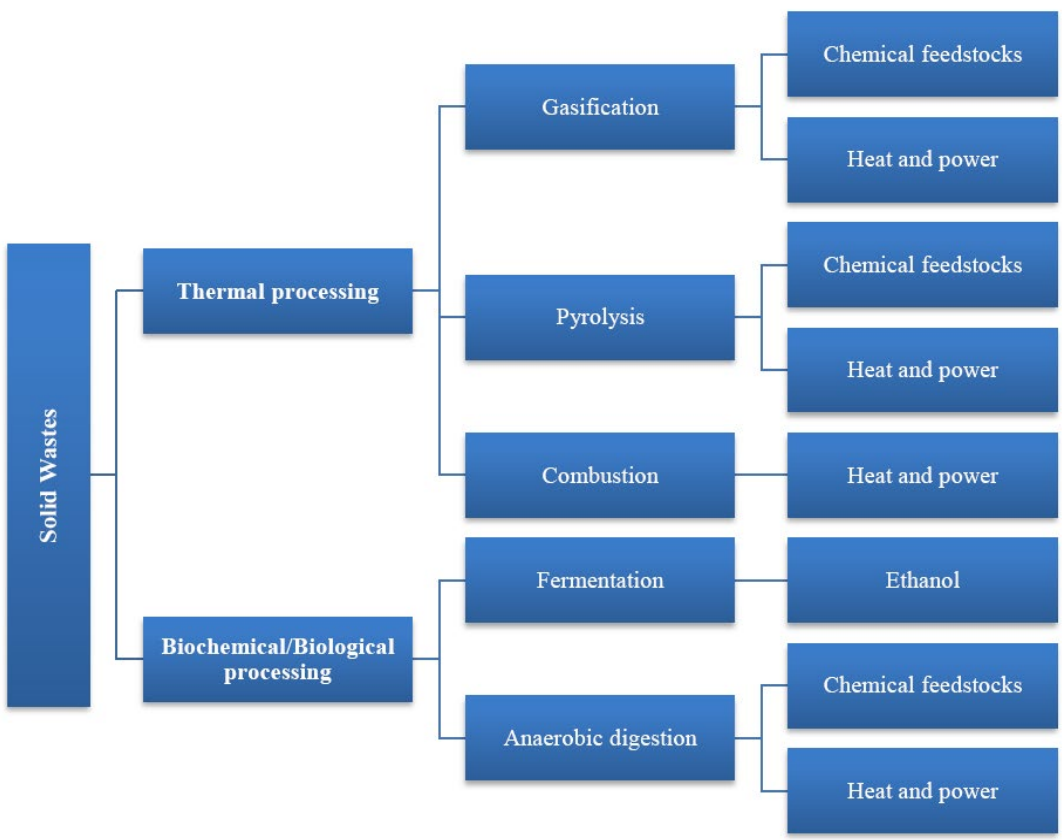

Figure 2. Solid waste to energy pathways (Auckland Council, 2011)

or electrical energy (Moustakas and Loizidou, 2010). Most of the facilities for MSW treatment do not ensure environmental safety due to capital cost limitations; but pyrolysis plants of proper capacity with energy products output are a suitable alternative when the quality of char, oil/wax, and combustible gases is under fine control (Chen et al., 2014). There are numerous pyrolysis plants that are being developed around the world. Globally in 2001, there were 100 small-scale pilot plants processing more than 4,000 tons of residue per year. Many plants are designed for specific processes such as separation and recovery services, and specific organic materials such as industrial by-products or residuals (Caruso et al., 2016).

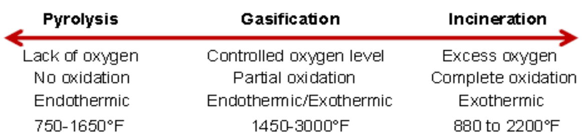

Figure 3. Thermal treatment of the MWS (Bridgwater, 1994)

Pyrolysis of biomass is an age-old technology and its application to MSW is a relatively recent development (Bridgwater, 1994). The feedstock (MSW) during pyrolysis will not thermally decompose before its moisture is vaporized. The total heat required for water vaporization is calculated according to the following equation:

$$Q = W \cdot 2260, [\mathrm{kJ/kg}] \quad (1)$$

where: W is the water content [%] of the feedstock to the reactor (Raveendran et al., 1996).

This is the reason that raw MSW feedstocks should be consistent, and it is usually not appropriate for pyrolysis. The MSW components with high moisture content such as food wastes, biomass are suggested to be separate before pyrolysis, therefore, the MSW needs mechanical preparation and separation of glass, metals, and inert materials (such as rubble) prior to processing the remaining waste (Scheirs and Kaminsky, 2006).

The reaction of thermal degradation of organic material that take place in pyrolysis process can be expressed as:

$$C_xH_yO_z + Q = Char + Liquid + Gas + H_2O \quad (2)$$

where: Q is the heat that needs to be input to the reactor for the reactions to take place.

The pyrolytic products of degradation of organic part of the waste are 75 - 90 % volatile substances and solid residue (coke) by 10 - 25 %. Humidity and inorganic substances present in the MSW decrease the volatile products and the quantity varies from 60 to 70 %, but increase the coke formation from 30 - 40 % (Chakraborty et al., 2013).

Pyrolysis processes have significantly lower pollutant emissions compared to normal combustion in the incinerator (Rumyantseva et al., 2017). It is necessary to prepare MSW for the process of pyrolysis, and needed stages include the following:

1. Sorting,
2. Size reduction,
3. Drying up to a certain moisture degree at 100 - 200 °C,
4. Pyrolysis process itself,
5. Separation and refining of volatile products and
6. Gasification.

The most important parameters affecting MSW pyrolysis are types of MSW, reaction temperature, heating rate (HR), residence materials' size, the usage of catalyst, the type of reactor and etc. There are different types of pyrolytic processes in accordance with the pyrolysis temperature (Rehraha et al., 2016; Rumyantseva et al., 2017):

- **Low-temperature pyrolysis is carried out** in the temperature range of 450 - 500 °C. The yield of different oils, tars or resins, and solid residue is maximum, and the lowest amount of gases is formed;
- **Medium temperature pyrolysis** is performed up to 800 °C. This type of pyrolysis increase the gas and oils formation and the volume of resins, but the residue is reduced;
- **High-temperature pyrolysis** treats unsorted MSW at temperatures above 800 °C and it is limited to 1050 - 1100 °C because residues (slag) melt and that can complicate the work of slag removal system. The maximum degree of gases is generated, but formation of resins, oils, and solid is minimal. Efficiency reaches up to 95 % (Bugayan, 2015);
- **Plasma pyrolysis** is used for hazardous waste disposal at a very high temperature, over 1000 °C, using plasma torches, where the synthetic gas with the optimum composition (mainly CO and H_2) and other end-products, such as a vitrified matrix, are formed (Miandad et al., 2016). This process needs lower reaction volume, but a large amount of secondary energy (example: 1 kWh/kg for arc plasma (Hauk et al., 2004)).
- **Microwave pyrolysis** is performed for homogenous MSW wastes (sludge, plastics, and tires) with very fine particles. The main advantages are rapid heating, easy control of the process, and maintenance of the desired temperature for desired product raising. The disadvantages are small treatment capacity, and impossibility to apply it on heterogeneous MSW, because accurate dielectric data in the microwave frequency range is a function of temperature, and

it is not available for most of the waste components (Yin, 2012).

The most MSW pyrolysis processes have been conducted at atmospheric pressure in typical fixed-bed reactors with a slow heating rate (HR). Vacuum pyrolysis has only been reported in studies of special wastes, such as printed circuit board (Pan, 2012). Another frequently used reactor is the more efficient rotary kiln for conventional (slow) pyrolysis with slow heating rate up to 100 °C/min and 1 h residence time. This type of reactor has good mixing of MSW, the flexible adjustment of residence time, simple maintenance, and larger channel for the entrance of waste, so extensive pre-treatment of wastes is not required (Li et al., 2005). Fluidized bed reactors with high HR and good blending of MSW are more frequently used for fast pyrolysis, and some innovative reactors are used as well (Dai et al., 2001).

The pyrolysis technology for MSW treatment with rotary kiln as pyrolysis reactor can be represented as shown in Figure 4. This is typical energy efficiency, commercially available technology in Europe.

4.1. Pyrolysis products as an energy source

All pyrolytic products often have good properties as a fuel, so they are desired easy to sell products because of their possible conversion to electricity or incineration. The formation of different products is very dependent on the reaction temperature. In a typical pyrolysis process the following reaction takes place: Initial decomposition of substances starts at 250 °C, and also decomposition of H_2S and CO_2. Decomposition of aliphatic bonds and separation of CH_4 and other aliphatic substances start at 340 °C. Enrichment of the produced material in carbon is at 380 °C. Breaking of C-O and C-N bonds occurs at 400 °C. In temperature range of 400 - 600 °C, a conversion of coal tar into fuel and tar happens. Higher temperature (> 600 °C) results with aromatic substances formation and hydrogen removal (Moustakas and Loizidou, 2010).

The composition, yield, and gas heating value of pyrolytic products are strongly dependent on the pyrolysis temperature, feedstock, and heating rate. Increasing the temperature causes increasing of gas yields, due to the second reaction and partial char decomposition (Dai et al., 2001). The gas heating value varies from 10 - 15 MJ/Nm^3 for slow and 14 MJ/Nm^3 (CO, H_2) for fast pyrolysis of biomass, where PP and PE is in range of 42 - 50 MJ/kg (H_2 and light hydrocarbons), and the pyro-gas from MSW consists of CO_2, CO, H_2, and other light hydrocarbons with average heating value around 15 MJ/Nm^3 (Jung et al., 2010). The liquid fuel can be used for the production of heat, electricity, synthesis gas, or chemicals. The heating value of pyrolytic oil from biomass is around 15 - 20 MJ/kg and 30 - 45 MJ/kg from a plastic polymer, and it contains less aqueous fraction (Adrados et al., 2012). In general, the liquid products of co-pyrolysis of biomass and synthetic polymers have the greatest heating value in the range of 41.33 - 46.4 MJ/kg, so they could be a valuable fuel resource (Rutkowski and Kubacki, 2006). The solid product or char is a carbon-rich matrix that contains almost all the inorganic compounds present in MSW, and it has around 33.6 MJ/kg heating value, which is comparable with typical coal (Chen et al., 2014).

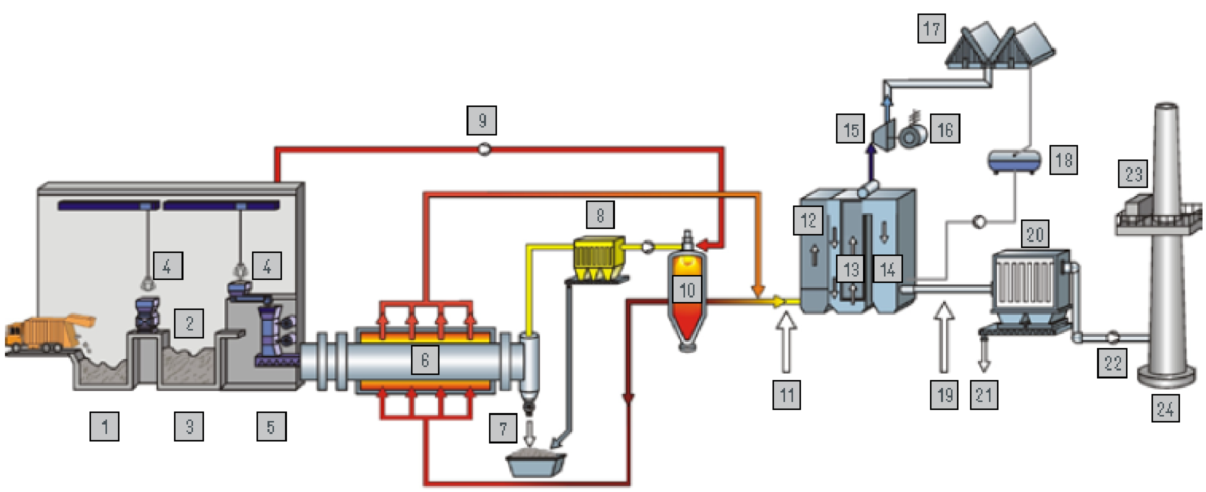

Figure 4. Schematic flow sheet of pyrolysis plant for special solid waste treatment

Agenda: 1. Coarse refuse bunker; **2.** Rotary shears; **3.** Fine refuse bunker; **4.** Overhead crane; **5.** Feeding system; **6.** Pyrolysis kiln; **7.** Discharging system; **8.** Hot gas filter; **9.** Combustion air fan; **10.** Combustion chamber; **11.** Selective non catalytic reduction; **12.** Evaporator; **13.** Super-heater; **14.** Economizer; **15.** Turbine; **16.** Generator; **17.** Condenser; **18.** Feed water tank; **19.** Additive metering hopper; **20.** Fibrous filter; **21.** Filter dust discharging; **22.** Induced ventilator; **23.** Emission monitoring system; **24.** Stack

4.2. Advantages and disadvantages of pyrolysis

There are many advantages of pyrolysis in comparison to incineration, seen as two different thermal technologies. The lower temperature is requisite and the decomposition takes place in the inert or reducing atmosphere, so there are fewer air emissions in the case of pyrolysis. The ash content in carbon is much higher than in incineration, and the metals in the ash are not oxidized, so they have a higher commercial value. The initial waste volume is reduced at a higher level in comparison to the incineration. Low demands for land for their installation and easy control of the process are also seen as advantages for the pyrolysis process (Malkow, 2004).

The main disadvantages of pyrolysis include the necessity of MSW pre-treatment, cleaning of gases, and wastewater treatment, which increase the cost of pyrolysis plants. The pyrolysis products cannot be disposed without further treatment, and the application of this method is limited to large scale. Demand for high quantities of waste, especially for incineration, and need for specialized personnel are also viewed as disadvantages (Chen et al., 2014).

4.3. Economic aspects

Pyrolysis and gasification as a thermal technology are the most expensive processes due to their high costs of investment, operation, and maintenance. The payback period for the investment is long, but the investment in the future in terms of achievements of the current and deferred environmental impact for future generations is also needed. Table 3 offers an orientation on the costs for an alternative technology plant with an annual input of 150,000 - 200,000 tons.

The analysis of the economic efficiency of high-temperature pyrolysis and gasification for MSW processing is attractive and appropriate for implementation due to environmental benefits. The main environmental benefit is the recycling of accumulated and newly generated waste and prevention of environmental damage. The economics of these technologies can only be considered as acceptable if the result of process is fuel (gas, liquid and, coke), which has a good market value. This depends very much on market conditions. The combined pyrolysis & gasification technology is a good choice for MSW treatment method in cities that can afford it. Pyrolysis alone, in general, is cheaper and may be adapted to the undeveloped places (Rumyantseva et al., 2017).

4.4. Comparison among thermal technologies

Thermal MSW processing is a part of a sustainable waste management system. Today, combustion is still the main thermal technology used for waste to energy conversion. Pyrolysis and gasification processes have many advantages, but they are more costly and more complicated processes. Thermal waste management methods should be applied together in order to maximize material recovery from waste. Summarizing the main characteristics of the common thermal techniques for waste management, Table 4 presents the basic products and the main operating conditions.

Table 3. Example of comparative individual cost elements of pyrolysis plant in Germany (Tangri and Wilson, 2017)

Cost estimates of a pyrolysis/gasification plant in developing countries - figures are a rough orientation only						
Initial Investment	Capital costs per ton and year of waste input	O&M costs per ton	Total cost per ton	Revenues* per ton	Cost** per ton waste input	Remark
80 - 120 Million EUR	35 - 45 EUR/t	30 - 40 EUR/t	65 - 80 EUR/t	2 - 5 EUR/t	63 - 80 EUR/t	Capacity 250,000 t/a, 20 y operation, 6 % p.a. IR

* From the sale of end-products ** Costs to be covered by gate fee, subsidies etc.

Table 4. Parameters of typical operation conditions & products of the common thermal management practices (Moustakas and Loizidou, 2010)

	Combustion	**Gasification**	**Pyrolysis**
Temperature (°C)	800 - 1450	500 - 1800	250 - 900
Pressure (bar)	1	1 - 45	1
Atmosphere	Air	O_2, H_20	Inert, N_2
Stoichiometric ratio	> 1	< 1	0
Products			
Gas phase	CO_2, H_2O, O_2, N_2	H_2, CO, CO_2, CH_4, H_2O, N_2	H_2, CO, H_20, N_2, HC
Solid phase	Ash, slag	Ash, slag	Ash, coke
Liquid phase			Pyrolysis oil, water

5. Conclusions

The global growth of municipal solid waste makes the urgent need to develop new and better methods of disposal. Different waste treatment options have different environmental impacts. Traditional methods like landfilling, composting, and incineration should be replaced by modern technologies due to their impact to the socio-economic and environmental issue. Thermal MSW technologies allow energy recovery, volume reduction, and conversion of hazard into non-hazard components of MSW, which makes these technologies environmentally friendly. The pyrolysis is thermal technology with the greatest potential. There are numerous successful commercial waste pyrolysis facilities operating worldwide, predominately in Europe and Japan.

The composition of MSW determines the technical efficiency of the pyrolysis technology. A good raw material for the pyrolysis process is basically any material, which includes organic carbon. A process parameters and type of reactor influence the yield and types of generated products. The obtained products of thermal treatment have high calorific value and are absolutely free of pathogenic factors due to the high temperatures process. Pyrolysis reduces the weight and volume of the treated waste and also, there is low requisite for land for installation of their units. In general, pyrolysis is characterized by relatively high operation cost, but they substantially decrease as the capacity of the plant increases.

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Proizvodnja održive energije iz čvrstog otpada putem postupka pirolize - pregled

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INFORMACIJE O RADU

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Savremena tehnologija

I Z V O D

Zagađenje životne sredine predstavlja glavni problem savremenog društva i povezan je sa brzom urbanizacijom i industrijalizacijom. Termički procesi, kao što je piroliza, razvijeni su da bi se smanjila količina otpada i da bi se zaštitila životna sredina. Postupak pirolize je optimizovan za proizvodnju goriva (u tečnom i gasovitom stanju, kao i ugalj) termičkom razgradnjom čvrstog otpada, bez prisustva vazduha.
Ova studija uključuje kratak pregled potencijala pirolize otpada. Piroliza se, kao termički proces, sa komercijalnog aspekta koristi u Evropi i Japanu. Fokus ovog rada su postupci pirolize koji uključuju količinu i vrstu proizvoda, konstrukciju reaktora, kao i ekonomičnost postupka. Prednosti i nedostaci postupka pirolize su takođe razmatrani u upoređivani sa postupkom spaljivanja koji se smatra sličnim termičkim postupkom.