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The use of thermal technologies for the recovery of value-added products from household solid waste: A brief review

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Abstract. The amount of household solid waste (HSW) has been significantly increasing due to a rapid population growth and economic development. HSW management is immensely sensitive and complicated problem not only in rapidly developing countries like Uzbekistan but also in developed countries with advanced economies.The accumulated waste has been causing a number of serious environmental problems such as release of the most dangerous greenhouse gases (CO_2, N_2O, CH_4) in the atmosphere which misbalance radiation in a planet's atmosphere causing a global warming. However, this waste can be friendly in terms of its potential to be used as energy source. HSW into energy conversion technologies has been playing a vital rolein order to successfully address global challenges suchas fossil fuel dependency, emission control and waste management issues.The most promising technology for conversions can be performed using thermochemical processes (e.g., pyrolysis or gasification).These thermochemical technologies can be used to convert solid waste into liquid and gaseous fuels, and this has already been studied sufficiently by other researchers. This article recommends a novel concept for intensification of value-added solid and liquid products recovery from HSW using hydrothermal carbonization and plasma treatment.

1. Introduction

A different sort of waste is constantly produced by mankind. Every year its quantity increases, along with an increase in consumption dynamics, in packaging materials, and filling landfills for waste storage. Waste and the way how societies handle them has led to a number of environmental problems, for example, the release of greenhouse gases, heavy metals and other environmentally harmful chemicals. Therefore, societies are trying to minimize their emissions to the open environment.

Household Solid Waste (HSW) is known to us as garbage, and it consists of food waste, paper, plastic, wood, glass, textiles, metals and others [1, 2]. Different types of waste and their main sources are shown in Table 1.

Table 1. Different type of wastes and their classification [3, 4]

Type of waste	Classification
Organic	rice, food, meat, vegetables, fruits, yard waste (branches, leaves, grass, brush), wood, bamboo, flowers, grass, processing residues, and other related wastes
Paper	paper waste, cardboard, newspapers, magazines, bags, boxes, wrapping paper, phone books, shredded paper, paper drink cups, and other related wastes
Plastic	plastic bottles, packaging, containers, bags, caps, plastic glasses, and other related wastes
Glass	glass bottles, broken glassware, light bulbs, stained glass, and other related wastes
Textile	clothes, cotton, chemical fiber, and other related wastes
Ferrous	metal cans, foil, cans, non-hazardous aerosol cans, appliances (white goods), railings, bicycles, and other related wastes
Others	leather, rubber, multilayer materials, electronic waste, batteries, household appliances, ash, other inert materials, and other related wastes

In addition, the composition of HSW depends on their location and its changing climatic conditions, as well as lifestyle [5]. For example, in Malaysia, HSW consists of wood waste (37.58%), food waste (16.32%), plastic bag (15.27%), hard plastic (14.57%), textiles (9.63%), glass (4.20%) and ferrous metals (2.42%) [6]; in Taiwan, paper (28.95%), cellulose fabric (8.11%), yard waste (3.10%), plastic (19.59%), leather and rubber (0.43%), glass (6.98%), metals (7.89%) and other (1.77%) [4, 5, 7]; in China, wood waste (2.94%), food waste (55.86%), non-combustible waste (18.36%), plastic (11.15%), textiles (3.16%), paper (8.52%) and rubber (0.84%) [8].

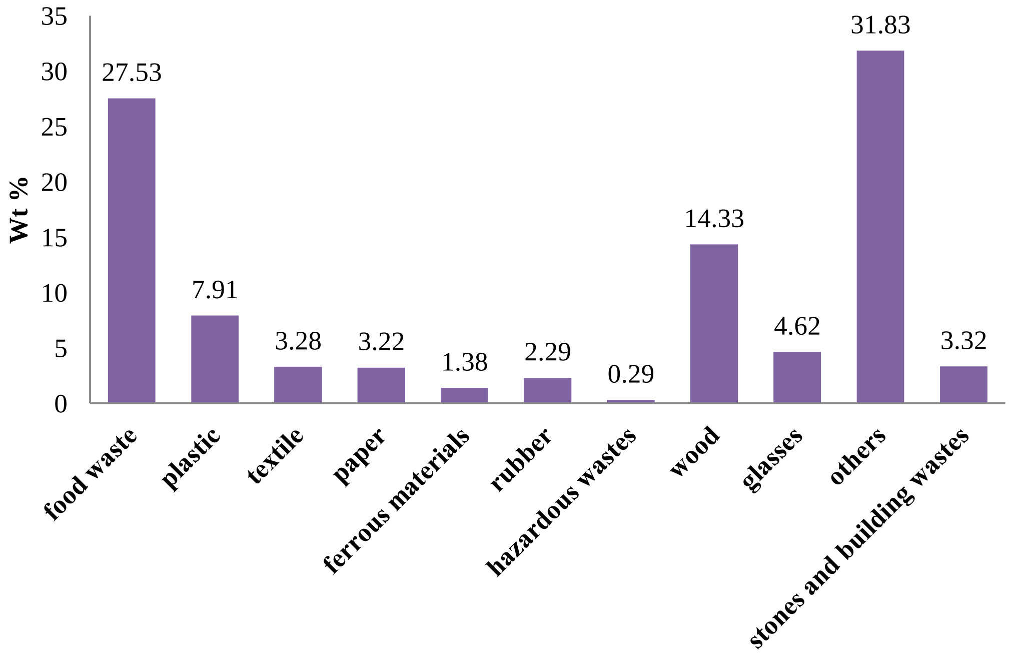

Figure 1. HSW composition in Uzbekistan (2017-2018)

In Uzbekistan, there are acute problems of the safe disposal of solid waste, as in the whole world. Annually, 35 million cubic meters of household waste and 100 million tons of industrial waste are generated in the republic. Today, 2 billion tons of solid wastes have accumulated in country's landfills [9]. Based on the results of studies conducted in 2017-2018, the HSW in the Republic of Uzbekistan was as follows: food waste, plastic, textile, paper, wood waste, rubber, glass, metals, hazardous household waste, stones and construction waste, as well as other small-fraction waste and their percentage is shown in Fig. 1.

Currently, the global growth of urban solid waste has become the biggest problem in developed and developing countries [10]. It should be noted that highly-populated countries such as China, India and the United States produce 170-200 [11, 12], 70 [13] and 254 million tons [5.14] of HSW per year, respectively. According to the World Bank's static data, 1.3 billion tons of HSW are produced worldwide and it is expected that this will increase to 2.2 billion tons by 2025 [15]. Obviously, such an increase in the amount of solid waste represents a negative impact on the environment and human health [13]. To minimize their impact on the environment and human health it is necessary to apply new approaches, such as the conversion of waste into value-added products and /or into one of the types of energy [16]. The energy extracted from the waste can be a source of energy for our home and vehicles [6], and can also be used to produce heat or electricity [17].

This paper discusses methods for converting waste into valuable products, such as combustion, pyrolysis, gasification, as well as new approaches, such as hydrothermal carbonization and plasma technology.

2. Thermal Treatment Methods of HSW

Traditional methods, such as incineration, composting and landfilling, are mainly used for the management and disposal of solid waste, and these methods have several disadvantages. In addition, they negatively affect the environment.

Since the end of the 19th century, incineration has been one of the most widely used thermal methods to reduce the amount of household waste [18–20]. Incineration reduces the mass and volume of household waste, and also the generated thermal energy can be used in the central heating system, as well as in the production of electricity as an additional source of energy. However, as a result of this process, such shortcomings arise as the emission of harmful substances into the atmosphere and the loss of valuable organic substances contained in household waste [19, 21].

For these reasons, today new approaches such as gasification and pyrolysis for converting waste into energy or valuable products are becoming increasingly popular as waste management methods.

The gasification process usually occurs at a temperature of 800 - 1200 ^{o}C and this process depends on the composition of the feed and the type of reactor [16]. As a result of this process, gas synthesis is performed -hydrogen, carbon monoxide and methane, but the process of purification of these gases is complicated and requires higher costs for their transportation [22]. However, the gasification process is one of the most effective ways to reduce the volume and quantity of waste for the following reasons [23]:

- processing of large amounts of waste takes less time than traditional methods;
- reduces the demand for large areas for the collection and disposal of household waste;
- one of the most suitable ways to reduce (eliminate) hazardous wastes that pollute soil and groundwater;
- incinerators and combustion chambers can be replaced.

The advantage of a produced gas from the gasification technology over a gas from biogas plants is its high calorific value [24]. Today, experiments, mathematical modeling and many studies are aimed at a better understanding and study of the gasification method [24-26]. Tar, which is a condensed mixture of high molecular weight hydrocarbons formed during gasification, is a serious problem and can cause damage, corrosion and clogging of the gas reactor [16]. However, various tar removal methods, such as physical [27], chemical [28, 29], catalytic [2, 6, 22], and the recently used steam gasification method, were used to reduce tar formation and increase hydrogen yield [30].

Pyrolysis is a thermochemical process that occurs at a temperature of 300 to 650 °C. As a result of combustion in an oxygen-free environment, biomass is transformed into liquid (biofuel), gas, and solid residue (bio-char) [31, 32]. Biofuels, gases and semi-coke are the main products of this process. The possibility of obtaining by-products of three types (biofuels, gas and semi-coke) leads to wider application of this process than other thermochemical processes (combustion, gasification) [5]. The volume and chemical composition of the secondary product obtained by pyrolysis depends on a number of parameters, such as the nature of the raw material, process temperature, and heating rate [5, 16]. Depending on the heating rate, the pyrolysis process is divided into slow and fast pyrolysis. With fast pyrolysis, the process proceeds in a very short time (several seconds) and secondary products, such as biofuels and gas, are obtained. Slow pyrolysis, on the other hand, takes a relatively long time (several minutes or more), and the secondary product are semi-coke, gas, oil and bio-char [33]. In addition, pyrolysis with a high heating rate, known as flash, is currently successfully used in laboratory conditions to produce synthesis gas (syngas) from solid fuels obtained from household solid waste [34]. Another new type of pyrolysis process is microwave pyrolysis. In this process, the heat released for the combustion of raw materials, is sent to its center by microwaves, so there is no need to shred the raw materials [5.16]. The main advantages of microwave pyrolysis are a relatively short combustion time, uniform combustion of the raw material, high thermal value of the volatile product [35] and the absence of the need to shred the raw material, which reduces additional costs [5].
However, the presence of methane and other organic compounds in the gas, obtained as a result of pyrolysis (gasification), reduces the possibility of its direct use [36]. To overcome this problem and increase the amount of obtained product, many scientists conduct experiments to create various catalysts. For example, Tursunov (2014) [6] used calcined dolomite and zeolite as catalysts for the pyrolysis / gasification of household wastes and studied their effect on the amount of gas produced as a result of the process. The amount of gas generated as a result of pyrolysis of household waste in the temperature range of 200 - 750 ^{o}C was observed in the range of 49 - 57 mol%. From the results of the experiment, he concluded that the use of properly calcined dolomite as a catalyst has a significant effect on the amount and composition of gas formed as a result of the process. Figure 2 shows a comparative diagram of the volume of the product obtained by using the catalysts which were tested by Tursunov (2014) [6].

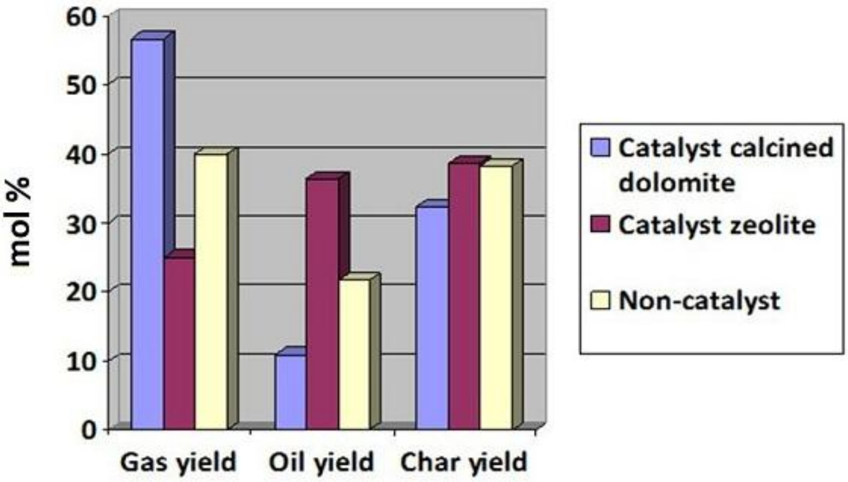

Figure 2. Comparative diagram of volumes of products (gas, oil, char) obtained by catalytic and non-catalytic pyrolysis at 750 ^{o}C [6]

However, to use the catalysts in wide-scale, they must have the following advantages:
- effective in removing tar;
- if the resulting product is synthesis gas, the catalyst must be capable of converting methane into additional synthesis gas;

• be able to provide a reasonable ratio of synthesis gas for the planned process;
• The catalysts must be stable to prevent heating and carbon pollution;
• catalysts should be easily removable, strong and, most importantly, inexpensive [36].

3. Hydrothermal Carbonization

Hydrothermal carbonization is a thermochemical process that occurs in the temperature range from 180 °C to 280 °C over a period of time from several minutes to several hours [37-39]. This process can operate at lower temperatures than other thermochemical conversion processes, such as combustion, gasification, and pyrolysis, and the use of water as a reaction medium means that the initial drying of biomass is not necessary [40, 41]. In accordance with this process, wet biomass, agricultural and household waste will be treated at high temperature in compressed hot water. In 1958, Leibniz [42] showed that H_2O (water vapor or water) should be used in hydrothermal treatment [42]. Using the van Crevelen diagram, it is possible to depict the effects of time and the temperature of the hydrothermal carbonization process. In addition, this chart is used to evaluate the energy quality of solid fuels (hydrocarbon). This diagram is shown in Figure 3 [43, 44].

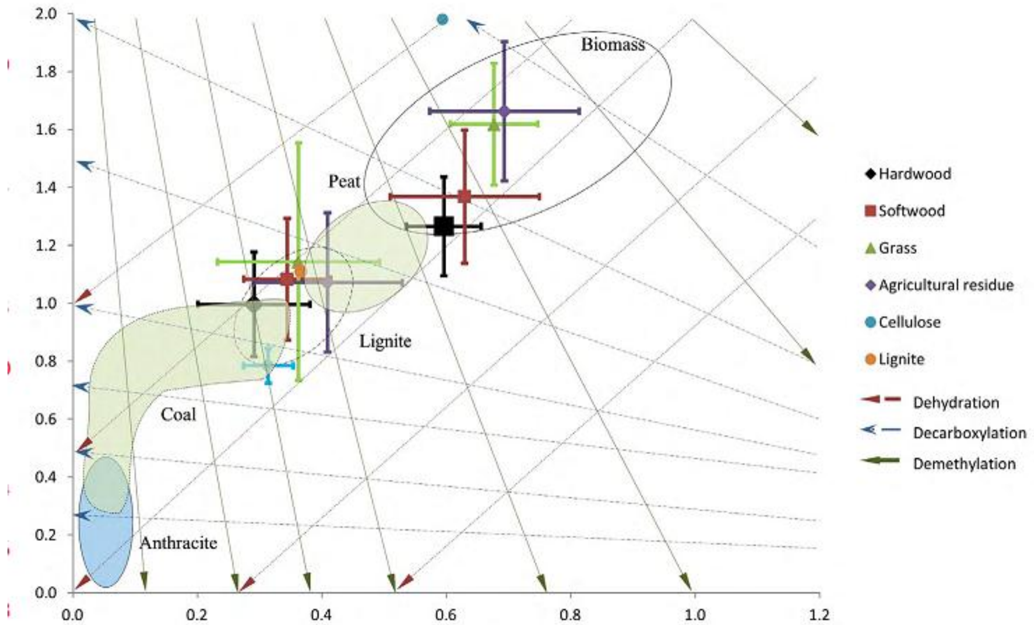

Figure 3. van Krevelen diagram of hydrochar from various feedstock with major reaction lines [43]

Among thermochemical processes, the advantage of hydrothermal treatment is that it is highly effective in converting biomass to solid products at relatively low temperatures [40]. The process of hydrothermal carbonization leads to the formation of solid hydrocarbonate (hydrocarbon), liquid fractions, and small amounts of gas [41]. The main product obtained as a result of hydrothermal carbonization is called hydrocarbon, and it can be used instead of coal in coal-fired power plants. In addition, the presence of a large amount of stable carbon and other nutrients in the hydrocarbon allows it to be used as a necessary additive component for fertilizing the soil. As a result, soil fertility may increase [43]. The hydrocarbon has a higher energy density relative to its mass of the starting material. For example, the energy and mass ratios of solid waste, food waste, and bird manure are between 14 and 18.1 MJ/kg, which is between 20 and 29.1 MJ/kg for hydrocarbon [45.46].
During hydrothermal carbonization, biomass waste such as coconut and rice sawdust [41], bird manure [46], coconut fiber and eucalyptus leaves [40], as well as human excrement [37] were used as raw materials. For example, Spitzer et al. [37] used human excrement as a starting material in hydrothermal carbonization. They carried out research work at three different temperatures (180, 210,

240 °C) and three types of reaction time (30, 60, 120 minutes). The results of the study showed that with an increase in the amount of raw materials, the yield of hydrocarbons decreased from 69 to 56%, and at the same time, the high energy value (heat capacity) increased from 24.7 to 27.6 MJ/kg. Based on these results, they came to the conclusion that the reuse of nutrients using the hydrothermal closed-loop carbonization method will provide sustainable results in resolving the sanitary energy problems.
Consequently, the possibility of processing in a relatively short time, food sterilization, pharmaceuticals and endocrine disruptors, such as micro-pollutants, are the advantages of this process as a solution to waste recycling alternatives [37]. In addition, it is an energy-efficient technology [48, 49].

4. Plasma Technology

The technologies known today in the field of solid waste processing, such as incineration, composting, pyrolysis, gasification [18, 50] and the aforementioned hydrothermal carbonization process, have several advantages as well as certain disadvantages. Apparently, waste is organic (food, vegetable waste, etc.) and inorganic (textile, glass, metal, etc.), as well as medical waste, polychlorinated biphenyl (PCB), hazardous waste such as ammunition, coal waste, thermal batteries and low-level radioactive waste [51]. Plasma technology, which is currently being described as a relatively new technology, has the ability to vaporize any chemical compounds and break down waste at the level of small elementary particles, which makes it possible to process the above types of waste and use them as secondary raw materials [21, 51]. Therefore, scientists around the world are currently working on a number of scientific and practical measures to develop this technology and bring it to a new level. Below we highlight a number of scientific studies conducted in the field of solid waste management using this technology.
Plasma is the fourth form of matter, consisting of free electrons, ions, and neutral particles, after a solid, liquid, and gaseous state [18, 49, 52-54] and can be detected in nature on the surface of the Sun and lightning [21]. As Ruj and Gosh [52] noted, the plasma is divided into thermal, cold, and thermal (intermediate) types. Among these types of plasma, thermal plasma is characterized by a high energy density and the properties of heating, melting and, in some cases, evaporation of the processed material (for example, household waste) at high temperatures. Thermal plasma, used in the processing of biomass waste, is generated using electric discharges of direct current 10^5 A, alternating current or a transient electric arc (lamps, circuit breakers or pulsed electric arc), as well as high-frequency and very high-frequency electric discharges at atmospheric pressure [54] .
At this point, we consider the process of plasma generation, as well as the structure and principle of operation of the plasma reactor used to remove waste. The electrodes in plasma reactors are supplied with a high current generator (10^5 A), which leads to a process known as electrical interruption due to a certain distance between the electrodes in the gas medium (air, steam, oxygen) inside the reactor [54]. A large current flowing through the electrodes is heated due to the electrical resistance of the metal electrodes and, as noted above, heat is released equivalent to 5000-8000F (2760-4427 ^{o}C), which has the property of decomposition of solid waste with the aim of elementary levels of particles [51]. In addition to the reactor, plasma equipment is used in several systems for processing solid waste; a waste delivery (transportation) system, a recycling chamber, a solid waste processing and disposal system, a gas control system, operational control, data collection and monitoring are formed [54].
As described in [50], plasma devices, used in waste disposal, have two different configurations (structures). In the first case, an electric arc is formed in the combustion chamber, which turns into a plasma in a gaseous medium. In the second case, solid waste is placed in an electrically grounded metal container used as an anode, and the material exposed should be electrically conductive [55].
Thus, the principle of operation of a plasma reactor is as follows: with a decrease in the volume of raw materials, primary processing is carried out to sort valuable raw materials, and then the waste is sent to a plasma reactor operating in an oxygen and high-temperature environment. In this environment, organic waste is converted to 95-99% into high-quality synthesis gas [51, 52, 56], and non-

decomposable inorganic waste changes its properties, that is, the solid substance leaves the reactor in liquid form and ultimately produces high-quality and harmless slag which can be used in construction. The resulting synthesis gas at a temperature of 1273-1473K is cooled through a heat exchange system to a temperature of 673K. During cooling, this heat is used to boil water in steam boilers and to generate electricity using steam generators by using the generated steam pressure [50, 56]. The resulting energy is mainly used to power plasma generators. Since, as noted in many literary sources, such as [2, 50, 52, 54, 56], the biggest drawback of this technology is the large amount of electrical energy needed to generate an electric arc. However, another one of the main disadvantages of this technology is that it requires a large initial investment [18].

Nevertheless, any technique and technology has its advantages and disadvantages, so this technology also has the following advantages:

• thermoplasma can process low-level radioactive substances, medical waste and similar hazardous wastes;

• has ability to process large amounts of waste using a small reactor due to the high temperature and energy density generated by the thermoplasma;

• high density of current generated in the reactor using plasma can effectively reduce the start-up and shutdown times of the device;

• a reactor does not require additional oxidizing agents in the formation of a heat source, and this leads to a decrease in the amount of gas necessary for the formation of plasma, which allows the whole process to be environmentally friendly, cost-effective and easy to manage;

• a high temperature generated in the reactor has the property of destroying oxides in polymer waste [52].

Therefore, from the aforementioned data, it became clear that the main disadvantage of high-temperature thermoplasma is that it requires a large amount of electrical energy. Therefore, today, microwave plasma technology is attracting attention due to its simple structure, compactness, low weight, uniform heating properties, applicability at atmospheric pressure and, most importantly, low energy consumption [18, 57, 58]. For example, Figure 4 shows an experimental schematic diagram of microwave plasma gasification, which was used by Hong et al [59] in their studies.

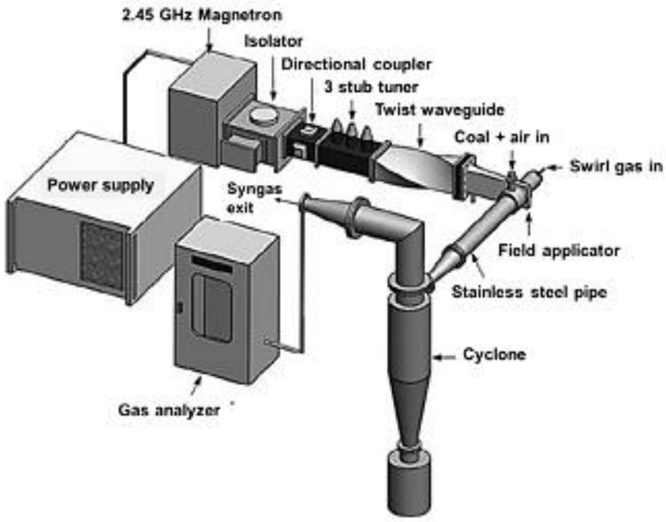

Figure 4. Experimental schematic diagram of microwave plasma gasification [59]

Based on the data presented in many publications, it can be said that today's studies on the disposal of solid waste based on plasma technology are mainly based on process parameters (reactor power consumption, amount of waste capacity, size, humidity, etc.) that affect the amount of product (synthesis gas). The following is a summary of the scientific work carried out in this field in recent years.

Luca Mazzoni et al. [56] found that it was possible to receive 81 MW of electricity per day from a mixture of two different wastes (household solid waste and oil industry waste) in a ratio of 90:10, respectively. The following authors [60-62] studied the coefficient of conversion of a material into synthesis gas depending on the amount of energy consumed by a plasma reactor, and concluded that the formation of synthesis gas increases depending on the power consumed by the reactor.
To find out whether waste size is one of the important parameters in productivity, Huang et al [63] studied tire residues in the range from 200 mm to 600 mm and found that a decrease in gas productivity was found during plasma gasification with an increase in tire residue size.
Rutberg et al [64] studied the effect of various gases used in plasma formation on wood waste with moisture content of 20% and found that air is the simplest and most suitable gas for gasification.
Khlina et al [65] investigated the plasma gasification of wood residues, plastic, and petroleum products in their scientific work. At the end of the study, it was noted that wood waste has a relatively high efficiency, close to the result of plastic wood waste, and the results obtained from oil waste was the lowest.

5. Conclusions

Today, traditional methods such as incineration, composting and landfill are used to dispose of household waste and reduce its negative impact on the environment. However, they are not very helpful in eradicating the problem of solid waste management. Therefore, along with traditional methods, new and relatively effective methods are used today, such as gasification, pyrolysis, and hydrothermal carbonization. In addition, plasma technology has attracted the attention of many scientists who are considered this technology as relatively environmentally friendly and energy efficient. As indicated above, the simplest and most common method of waste disposal is incineration. As a result of combustion, thermal energy is obtained, which is widely used in steam boilers and in heating systems for boiling water. This process is able to reduce the volume of waste by 90 - 95%, but the biggest drawback of the process is the release of toxic gases into the atmosphere containing waste.
As a result of the pyrolysis/gasification process, household waste can be recycled at high temperatures to produce by-products such as biofuels, gas and bio-char. During the gasification process, gases such as hydrogen, synthesis gas, carbon monoxide and methane are formed. Its biggest drawback is the complexity of the process of purification of these gases and the high cost of their transportation. The advantage of the pyrolysis process than gasification is that in addition to obtaining gas, it is possible to obtain additional products, such as bio-char and biofuels. However, common disadvantages of the pyrolysis / gasification process may include the need to pre-sorting and shredding the waste before processing it. This, in turn, will lead to an increase in costs. In addition, the release of tar is also one of the main problems of these processes.
As indicated above, one of the methods for processing HSW is hydrothermal carbonization. The advantage of the hydrothermal carbonization method is that the process is carried out at relatively low temperatures and in the aquatic environment. The use of water as a reaction medium of this process, waste does not require drying before it, and this, in turn, will lead to lower costs. The product of the process is hydrocarbon and can be used as coal.
Plasma technology is the most efficient way to recycle this waste. Because the very high temperature of the plasma allows it to vaporize various hazardous and chemical compounds present in the waste, and decompose at the level of small elementary particles, and also produce electricity and by-products. However, the biggest drawback of plasma technology is to create a plasma arc which requires a large amount of electrical energy. In addition, this technology requires high initial capital costs.
To sum up, each method has its advantages and disadvantages. Therefore, modern research in this area is aimed at achieving high efficiency at low cost.

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