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THE AMERICAN UNIVERSITY IN CAIRO
الجامعة الأمريكية بالقاهرة

School of Sciences and Engineering

**Investigating the use of solid waste as Alternative
Fuels in Egypt**

By

Fatma A. Shahat

A thesis submitted in partial fulfillment of the requirements for
the degree of

Master of Science in Environmental Engineering

Under the supervision of

Prof. Salah M. El-Haggar

Dr. Ahmed S. El-Gendy

Fall 2016

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Abstract

Every year Egypt produces enormous amounts of solid waste that reached 89 million tons/year in 2012 and still in continuous increase. As most experts agree, waste can be a hidden treasure for the nation, if it is fully exploited. Indeed, solid waste can be reused, recycled, or even recovered as a source of energy instead of simply being disposed in dumpsters and landfills. Given the need for alternative sources of energy, energy crisis, and waste management problems in Egypt, waste-to-energy (WTE) seems to be an optimum solution for both problems: energy and waste disposal.

In the first phase of this research, a comparative study was conducted to investigate the average calorific value of various waste materials from agricultural, industrial, and municipal waste sources including six types of plastics, tires, sawdust, rice straw, rice husk, corn husk, bagasse, and onion leaves. Due to the fact that biomass pellets are more uniform, and easier to transport and store, the second phase of the study investigated the use of starch, water, and Ca(OH)_2 as binders for biomass pellets and their impact on the average calorific value. The final phase investigated the emissions produced from the most promising waste materials.

The results showed that among the six types of plastics, polypropylene (PP) has given the highest average calorific value, while bagasse had a maximum average calorific value among the five investigated agricultural wastes. Rice straw can also be one of the promising agricultural WTE materials in Egypt because it is abundant in large quantities; same as tires which are widely available and have high average calorific value when compared to fossil fuels like coal and diesel. From the second phase, the utilization of starch, water, and Ca(OH)_2 had a minor impact on the average calorific value of the investigated biomass with a maximum decrease of 10% of the original calorific value, however, this percentage

changed from one material to another. In the third phase, emissions measured were CO, NO, NO₂, CO₂, and SO₂ for rice straw, bagasse, tires, and polypropylene, which were selected based on the first phase results. Emissions were measured using Testo gas analyzer that only provided rough estimation of emissions and only comparative figures. The results showed that tires had the highest mass of SO₂, CO, and CO₂ per unit mass of tires, while bagasse had the maximum NO value. NO₂ was almost the same for tires and bagasse, and they gave the highest value of NO₂. However, the produced emissions could have been impacted with the percentage of mass loss in the combustion process, and other pollutants that could not be measured in this study. The results obtained can be used for industrial application, especially for energy-intensive sectors that can use waste as a source of energy because it includes the average calorific values of different materials, which is one of the most important factors that should be taken into consideration while evaluating WTE materials, as well as the produced emissions from the most promising ones. Determining these emissions would help those industries to decide on mitigation and removal technologies that can be used in order to reduce those emissions.

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Acronyms

AF	Alternative Fuels
ANP	Analytic Network Process
bcm	billion cubic meter
bdRDF	Binder densified RDF
BFBR	Bubbling fluidized bed
BTU	British thermal units
Ca(OH) ₂	Calcium hydroxide
CEN	European Committee for Standardization
CHP	Combined heat and power
CO	Carbon monoxide
CO ₂	Carbon dioxide
CV	Calorific value
dscm	Dry standard cubic meter of stack gas
EPA	Environment Protection Agency
ESA	Energy system analysis
FBD	Fluidized bed combustion
GHG	Greenhouse gases
HCl	Hydrochloric acid
HDPE	High density polyethylene
LDPE	Low density polyethylene
MACT	Maximum Available Control Technology
MCDM	Multi Criteria Decision Making
MCFC	Molten carbonate fuel cells
MEP	Mediterranean Energy Perspective

M _f	Moisture content of feeding material
M _p	Moisture content of pellets
MSW	Municipal Solid Waste
MT	million ton
mtoe	million-ton oil equivalent
NH ₃	Ammonia
NO _x	Nitrogen Oxides
NO	Nitric Oxide
NO ₂	Nitrogen Dioxide
PAHs	Polycyclic aromatic hydrocarbons
PCBs	Polychlorinated biphenyl
PCDD/F	Polychlorinated dibenzo- <i>p</i> -dioxins /dibenzofurans
PDF	Packaging Derived Fuel
PEF	Processed Engineered Fuel
PET	Polyethylene terephthalate
PFI	Pellet Fuels Institute
PM	Particulate matter
PP	Polypropylene
PPF	Paper and Plastic Fraction
ppmv	part per million volume
PS	Polystyrene
PV	Photovoltaic
PVC	Polyvinyl chloride
RDF	Refuse Derived Fuel
RDF-IMC	RDF from industrial, municipal, and construction wastes

RDF-IS	RDF from industrial sludge
RDF-MS	RDF from municipal solid waste
REF	Recovered Fuel
SLF	Substitute Liquid Fuel
SO _x	Sulphur oxides
SWM	Solid Waste Management
TDF	Tire derived fuel
TEQ	Toxic equivalent
USEPA	U.S. Environmental Protection Agency
VOC	Volatile organic compounds
WDF	Waste Derived Fuel
WHO	World Health Organization
WID	Waste Incineration Directive
WTE	Waste-to-Energy

CHAPTER (1)

INTRODUCTION

1.1 Energy Consumption

As a result of the industrial development and the ever-growing population all over the world, the global demand for energy has been increasing enormously. For so long, fossil fuels (non-renewable sources), such as coal, natural gas, oil-based fuels, have been the primary source of energy everywhere, which led to the fear of the depletion of such resources one day. About 80 % of the total energy used worldwide has been derived from fossil fuels, while 20 % only is obtained from renewable energy sources since the beginning of the 21st century (Selin, 2014). It is expected that the current reserves of petroleum will last during the twenty-first century if they are continued to be consumed at the current rates. Moreover, the discovery of new reserves has decreased as compared with earlier. Nevertheless, the coal reserves are much larger, but it can result in environmental catastrophes to extract it (The Gale Encyclopedia of Science, 2008). Furthermore, fossil fuel burning is considered as a main contributor to the global warming as it releases carbon dioxide, which is one of the main greenhouse gases. It also causes air pollution since large quantities of toxic matters are emitted such as sulfur dioxide, particulate matter, nitrogen oxides, and toxic chemicals. The exposure to such pollutants can cause several human health problems as well as the negative impacts on the environment like the acid rain that even affects the aquatic life and forestry (Selin, 2014)

From here, the urgent need for alternative sources of energy to replace fossil fuels has come out, in order to avoid the energy crisis as well as environmental disasters. Also,

the wider use of renewable sources of energy is seen as a key for more sustainable and affordable economy across the world (The Gale Encyclopedia of Science, 2008).

1.2 Non-Renewable Energy

Non-renewable energy sources are fossil fuels (oil, natural gas, and coal) and nuclear energy. Fossil fuels need millions of years to form, and they come out in the form of liquid, gas, or solids. Such non-renewable energy sources are expected to run out soon since they cannot be replenished in our lifetimes.

1.2.1 Oil

Oil is considered as hydrocarbons that were formed from animals and plants, which lived millions of years ago. Crude oil come out in the form of liquid and it exists in reservoirs or underground pools, near the surface in tar sands, or in tiny space within sedimentary rocks. Crude oil is then refined into different petroleum products including distillates like diesel fuel and heating oil, waxes, lubricating oils, jet fuel, gasoline, petrochemical feedstocks, and asphalt (U.S.EIA, 2016).

1.2.2 Natural gas

Natural gas is a gas that is composed mainly of methane, which is a gas with four hydrogen atoms and one carbon atom, and it also contains small quantities of non-hydrocarbon gases and hydrocarbon liquids. Natural gas exists deep beneath the earth's surface, and it can be used as a fuel or to produce chemicals and materials (U.S.EIA, 2015).

1.2.3 Coal

Coal is a combustible black or brownish black sedimentary rock that contains high amount of carbon and hydrocarbons. Coal was formed from dead plants that existed millions

of years ago by being subjected to heat and pressure. There are four main types of coal that are categorized based on the amount of carbon contained and the amount of heat energy that coal produces. The first type is anthracite that contains 86-97% carbon, and has the highest heating value among the four types of coal. Bituminous coal contains 45-86% carbon, while subbituminous coal typically contains 35-35% carbon and has lower heating value than bituminous coal. The fourth type of coal is lignite which contains 25-35% carbon, and has the lowest heat content of all coal types (U.S.EIA, 2016).

1.2.4 Nuclear energy

Atoms are split apart in nuclear fission, which releases energy. Most nuclear power plants use nuclear fission using uranium atoms. During nuclear fission, uranium atom is hit by a neutron and split causing release of large amount of energy as heat or radiation. When a uranium atom splits, more neutrons are released, and then they hit other uranium atoms and the process is repeated over and over, in a process called “nuclear chain reaction”. A specific type of uranium called U-235 is the most widely used fuel in nuclear power plants because its atoms can split apart easily. However, this kind of uranium “U-235” is relatively rare, and thus it is considered non-renewable energy. Moreover, it is still difficult to control a fusion reaction (U.S.EIA, 2015).

1.3 Alternative (Renewable) Energy

There is a current need to replace or substitute fossil fuels like oil, coal, and natural gas, and nuclear materials such as uranium, with alternative energy in order to avoid the expected consequences of the increasing usage of such non-renewable sources. Alternative energy is any form of energy that does not come from fossil fuels or nuclear energy. The term renewable energy can also be used instead of alternative energy, which is usable energy

obtained from renewable sources such as wind (wind power), rivers (hydroelectric power), sun (solar energy), hot springs (geothermal energy), tides (tidal power), biomass (biofuels), and waste (Selin, 2014). Such alternative sources still represent a small fraction of the total energy; however, their usage is rising rapidly (The Gale Encyclopedia of Science, 2008).

1.3.1 Wind power

Wind power has been used for thousands of years as it was first used in 5000 BC for the navigation of sailors in the Nile River. It was also used by Persians to pump water and grind grain through windmills. Nowadays, wind power is considered as “one of the most promising new energy sources that can serve as an alternative to fossil fuel- generated electricity”. Wind energy has become more available, affordable, and pollution-free; however, it has some disadvantages as it is deemed as a diffuse source of energy. It needs huge numbers of wind generators, and hence large areas of land in order to be able to produce significant quantities of electricity or heat. It is also costly to build and maintain a wind farm and not easy to find an appropriate windy place for such a purpose (Alternative Energy, 2015).

1.3.2 Hydroelectric power

Thousands of years ago, the Greeks used the movement of water “hydroelectric power” to produce energy; converting the kinetic energy into mechanical energy to pump water and grind grains. Moreover, the water wheel was used in the 1800s to power machines such as timber-cutting saws. In order to maximize the use of this energy, dams were constructed to enclose a part of the river as artificial lake or reservoirs. Afterwards, water can pass through tunnels in the dam, and such movement of water turns turbines and thus generators move to produce electricity (Hydroelectric energy, 2015). Hydroelectric power is

a clean, renewable, and inexpensive source of energy. However, the construction of such dams impacts the lives of the people nearby as well as the eco-systems (Hydroelectric power, 2015).

1.3.3 Solar energy

Solar energy comes from the nuclear fusion power from the core of the sun. It is an inexhaustible, and pollution and noise free source of energy. Solar energy was first used for heating water and cooking food in 1767 by a Swiss scientist. Later, it was found that the sunlight could be converted into electricity with an efficiency of 1-2% through photovoltaic (PV) cells in the 1880s. However, that conversion could not be understood until Albert Einstein explained the photoelectric effect in the early 1900s. Currently, the solar power is still used in the same two ways to convert light into heat and electricity through a system that is composed of cells. The photovoltaic power is pollution free, needs little maintenance, does not include moving parts that may break down, and has inexpensive running costs with a lifetime of 20-30 years. On the other hand, there are two disadvantages when using solar power, which are the cost of equipment and amount of sunlight. The amount of sunlight varies according to the time of day, seasons, clouds, and geographical location. Also, solar energy technologies are still more expensive than traditional sources of energy, although huge improvements in the technological and cost aspects have been done (Solar Energy, 2015).

1.3.4 Geothermal energy

Geothermal power comes from the heat inside the earth; such heat is very intense as it creates molten magma. If hot magma formed near the surface, about 1500 to 10000 meters deep, groundwater can be heated directly. When hot water and steam occur naturally, it can

be used to generate electricity or for hot water production to be used directly. This can happen through energy conversion technology. Even if magma is not near the surface, it heats rocks that heat the deep-circulating groundwater as well. For geothermal energy to be feasible, its concentration must be high at this location. Geothermal systems are most appropriate for locations that are geologically active, where well-developed thermal systems can be constructed. In Iceland, geologic plates move constantly in addition to the volcanic nature of the island, thus geothermal energy is used there to heat about 95% of homes. Earth energy is another type of geothermal energy that can be extracted from the shallow ground by heat pumps to directly heat or cool houses. Since the temperature under the ground tends to be at the yearly average, this is why the ground in winter is warmer than air and vice versa in summer. Therefore, earth energy is used to heat a building in winter and act as air conditioner in summer. However, geothermal energy is considered as a non-renewable source as it declines with time because steam is extracted faster than it could be produced naturally at that location. Geothermal energy has also some environmental impacts since some of its applications emit carbon dioxide and hydrogen sulfide (Geothermal Energy, 2015).

1.3.5 Tidal energy

Tidal energy is another source of renewable energy that is produced by the rise and fall of tides of ocean waters. Special generators are used to convert tidal energy into electricity, where there is a significant difference between high and low tide. However, tidal energy is not widely used, as the amount of power produced so far has been small. Also, investors are not eager yet about tidal energy because there is no strong guarantee that they will benefit from it (Tidal Energy, 2015).

1.3.6 Biofuels

Biofuels are fuels that are produced in direct or indirect ways from organic materials. There are two types of biofuels, which are primary (unprocessed), and secondary (processed). Primary fuels are used in their natural form such as firewood, wood chips and pellets. Those fuels are burned directly to produce electricity, or to supply cooking and heating in small and large scale industrial applications. On the contrary, secondary biofuels are used for different applications such as transport and high-temperature industrial applications. Secondary biofuels are present in the form of solids (like alternative fuels from solid waste), liquids (such as ethanol, biodiesel, and bio-oil), or gases (such as synthesis gas, hydrogen and biogas) (FAO, 2008).

1.3.6.1 Bio-Ethanol

Ethanol is the leading biofuel used currently. It is an alcohol derivative, and is also known as ethyl alcohol. It is obtained by the fermentation of sugars, and usually from the corn grains or other agricultural products. The most used form of ethanol in transportation is E85, which contains 85% ethanol and 15% gasoline. All flex-fuel light-duty vehicles are designed to use E85 (USDFTFA, 2006).

1.3.6.2 Biodiesel

Biodiesel is produced from animal fats or vegetable oils. A known type of biodiesel is B20 which contains 20% biodiesel blended with petroleum diesel. This mix gives the optimum benefits in terms of cost, risk of field problems, and emission benefits. B20 is widely used in diesel engines without modifications (USDFTFA, 2006).

1.3.6.3 Hydrogen

Hydrogen is a clean, and renewable energy source that cannot be depleted. Hydrogen is present in large amounts in water (H₂O), hydrocarbons such as methane (CH₄), and other organic matters. One of the challenges that faces the use of hydrogen as fuel is to extract hydrogen from such compounds efficiently. Hydrogen is a gas that can be obtained by electrolysis, which is a process of combining oxygen and water. Also, it can be produced from steam reforming, or combining high-temperature steam with natural gas. Most of the hydrogen produced in the U.S. is utilized in refining petroleum, producing fertilizers, processing foods, and treating metals. The process of hydrogen production may result in emissions that affect the air quality based on the source. However, fuel cell vehicles are zero-emission vehicles as they only produce water vapor as well as warm air as exhaust. Research and development efforts are still exerted to use such vehicles widely (Alternative Fuels Data Center, 2014).

1.3.7 Waste-to-Energy (WTE)

Another promising source of energy that has been known for a while is waste. Some of the abovementioned biofuels can also be considered as waste-to-energy (WTE) sources because they are obtained from wastes, such as organic waste. Waste fuels can be defined as “...waste that is used entirely or to a relevant extent for the purpose of energy generation...” as given in the “Waste Incineration Directive (WID)” (Sarc & Lorber, 2013). However, it is very important that recyclables are removed first and then energy can be recovered from the remaining part, i.e. residual waste. There are various WTE technologies that can be used, which are (Renewable Energy Association (REA), 2011):

- Combustion, where waste is burned and energy is recovered as heat or electricity
- Pyrolysis and gasification, in which “syngas” is produced by fuel heated with little or no oxygen. This syngas can be used to produce energy or as a feedstock to generate methane, biofuels, chemicals, or hydrogen
- Anaerobic digestion that converts organic waste into methane-rich biogas by using microorganisms. Biogas can be combusted to produce electricity and heat or converted into bio-methane. This technology suits wet organic wastes or food wastes the most, and it can also produce bio-fertilizer.

1.4 The Need for Waste-to-Energy (WTE)

The volume of solid waste produced worldwide has significantly increased due to a number of factors such as the ever-growing population, the increase in the standard of living in some developing countries, urbanization, and industrialization. As a consequence, solid waste management has become a major concern and challenge for communities: the issue is how to get rid of these wastes with the minimum impact on the environment. Several methods have been used to dispose different types of solid waste; each method has its advantages and disadvantages (Dong & Lee, 2009). The most common disposal methods are landfilling, recycling, composting, mechanical-biological treatment, and waste to energy (WTE) (Psomopoulos, Bourka, & Themelis, 2009). Among the different disposal alternatives, landfilling has been the most widespread, but it will be limited in the future because of the tremendous spaces needed, leachate problems as well as gas emissions. Moreover, bioremediation is only used for biodegradable waste that decomposes, and recycling cannot be applied for all types of wastes. On the other hand, thermal treatment with heat recovery (WTE) has become an attractive method, not only for waste disposal, but also for energy recovery in addition to many other advantages (Stehlik, 2009).

Incineration technology has been such a perfect alternative as it reduces the original volume by 90% and about 75% of the original weight of solid waste as well as the energy recovery (Dong & Lee, 2009). However, the main concern for WTE plants in the past was the production of ash, and the hazardous toxic pollutants released in the environment such as dioxins and furans. Nevertheless, this has been changed after the U.S. Environmental Protection Agency (USEPA) put the maximum available control technology (MACT) regulations into effect in the 1990s to lessen the adverse effects of WTE facilities on the environment. As a result, the emissions of WTE have been decreased to the extent that even led the USEPA to name WTE as one of the cleanest sources of energy in 2003 (Psomopoulos, Bourka, & Themelis, 2009).

Another major advantage for WTE is that it can be an alternate for energy sources in those countries that suffer from both fuel shortage and waste disposal issues (Dong & Lee, 2009). For instance, they used this solution in Korea because they faced problems in finding new spaces for landfills since waste resources increased and waste treatment capacities became inadequate. Moreover, they also had a lack in the natural sources of fuel or energy. One more thing is that WTE can be considered as a renewable source of energy; it can even lead to the goal of 20% renewable energy and 20% decrease in CO₂ emissions that was agreed upon at the European level (Munster & Lund, 2010).

1.5 Solid Waste in Egypt

Generally, Waste can be defined as what is left behind from whatever activity and it has no use at source anymore, however, it can still be valuable for other activities (Abou-ElSeoud, 2008). They can be classified based on their nature, their source of generation, or their hazardousness. Wastes are divided into several categories based on their source, which

are municipal, agricultural, industrial, construction and demolition, and medical wastes (SWEEP, 2014). According to waste nature, it can be solid or liquid waste. Our focus in this thesis is the municipal, agricultural, and industrial wastes. Municipal solid waste usually comes from residential, commercial, educational, and health facilities in addition to wastes from gardens, markets, hotels, and small factories and camps. Industrial solid waste contains hazardous components including chemicals and heavy metals resulted from medium to large industrial facilities. Agricultural waste is a result of farming activities, including crop remains that can be used for energy production, animal feed, fertilizers, or to be recycled. Furthermore, animal manure, pesticide residue, and agricultural fertilizers are considered as agricultural wastes, but they are hazardous and need special handling (Abou-ElSeoud, 2008).

The total solid waste in Egypt in 2012 is approximately estimated as 89 million tons/year (NILE, 2013). Table 1 shows the amount of generated solid waste in Egypt in 2012 based on the type and source of waste. Solid waste management (SWM) in Egypt is among one of the big challenges that the country faces due to the rapid urbanization and high population growth rate. However, the waste characteristics and quantities differ from one location to another even within the same country. In order to achieve the best waste management strategy, the characteristics, quantities, and components of the existing waste should be determined (UNEP, 2005). For instance, if the waste is of low-calorific value, then it cannot be incinerated without the usage of supplementary fuel.

Table 1 - Estimated generated solid waste in Egypt in 2012 (NILE, 2013)

Waste Type	Generated Quantity (Million tonnes)	%
Municipal solid waste	21.0	23.5
Industrial waste	6.0	6.7
Agricultural waste	30.0	33.6
Waterway cleansing waste	25	28.0
Medical Waste	0.28	0.3
Demolition and construction waste	4.0	4.5
Sludge	3	3.4
Total	89.28	100

1.5.1 Municipal solid waste (MSW)

Municipal solid waste (MSW) in Egypt was estimated with 21 million tons/year in 2012 (NILE, 2013). Figure 1 shows the composition of municipal solid waste in 2012. MSW is composed mainly from residential solid wastes, and also contains some non-hazardous commercial, industrial and institutional wastes (Energy Information Administration , 2007). The composition of MSW is organic matter as the largest percentage, and less percentages of glass, paper, plastics, and minerals. Municipal solid wastes may also contain some hazardous substances like chemicals, used dry batteries, household insecticides, expired medicines, paints, drug residues, and electrical and electronic devices (Abou-ElSeoud, 2008).

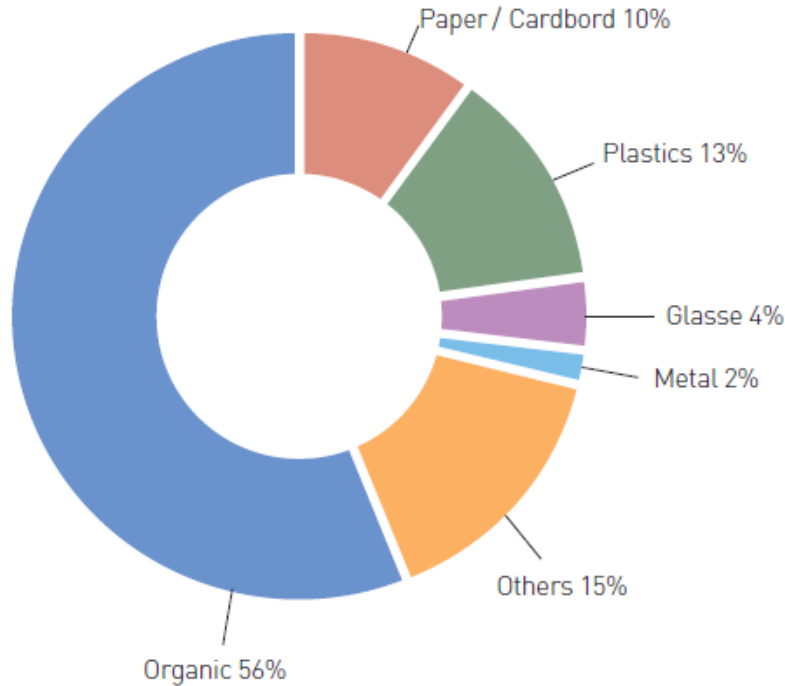


Figure 1 - Municipal solid waste composition in 2012 (NILE, 2013)

The disposal of MSW can be problematic because of its large volume (Energy Information Administration , 2007). The organic components can be composted for the improvement of the soil properties, recycled, or used to produce electricity from methane gas. The rest of components like plastics, paper, metals, and glass can be separated, and reused for manufacturing of similar or different products (Abou-ElSeoud, 2008).

There are different treatment methods for MSW based on its properties. The properties of MSW in Egypt determines whether it should be composted, recycled, converted to energy, or disposed in landfill. The relative density is almost 0.3 ton/cubic meter, humidity is about 30-40%, while the heat content is about 6276 kJ/kg (Genena, 2010). In order to solve that volume problem of the MSW, it can be combusted to decrease its volume in addition to creating energy that can be recovered in the form of heat or steam. However, the amount of energy that can be obtained from waste can be determined by the composition of the waste stream as some materials have higher heat content than others. For example, some

plastics have more heat content than yard trimmings or organic textiles.**Error! Reference source not found.** Table 2 shows the heat content for some materials in MSW (Energy Information Administration , 2007).

Table 2 - Typical heat content of materials in Municipal Solid Waste (MSW) (kJ/kg) (Energy Information Administration , 2007)

Materials	kJ/kg
Plastics	
Polyethylene terephthalate (PET)	23842
High density polyethylene (HDPE)	44194
Polyvinyl chloride (PVC)	19190
Low density polyethylene/ Linear low density polyethylene (LDPE/LLDPE)	28028
Polypropylene (PP)	44194
Polystyrene (PS)	41403
Other	23842
Rubber	312845
Leather	16747
Textiles	16049
Wood	11630
Food	6048
Yard trimmings	6978
Newspaper	18608
Corrugated cardboard	19190
Mixed paper	7792

1.5.2 Industrial solid waste

Most of the industrial waste in Egypt comes from the following industries: petrochemicals, plastics and resin, pulp and paper, food, cement, metallurgical, fertilizer, textiles, wood and furniture, chemical and pharmaceutical industries. These industries and others are considered as a major contributor to solid waste problem in Egypt. About 24,500 industrial facilities are distributed all over Egypt, however, approximately 50% are located in the Greater Cairo, and about 40% in Alexandria (USAID, EPP, & MSEA, 2009). The remaining facilities are in the Delta, Upper Egypt, and new cities like the 10th of Ramadan. The industrial solid waste can be classified into hazardous and non-hazardous waste. The generation of the industrial non-hazardous solid waste in Egypt is estimated with six million tons in 2012. In order to manage the industrial solid waste effectively, its quantity and physical characteristics should be determined (SWEET, 2014).

1.5.3 Agricultural solid waste

The agricultural solid waste represents the third environmental issue in Egypt, right after the sewerage and garbage problems. Agricultural solid waste is disposed in channels and drains resulting in contaminating the soil, groundwater as well as surface water (El-Haggar, 2004). In 2012, Egypt produced about 30 million tons of agricultural waste. The primary problem that obstructs the agricultural waste management is the lack of machines for combining, raking, and baling. Another problem is the shortage in the number of trucks needed to transport this waste as well as the unpaved roads. Therefore, farmers find that burning crop residues, especially rice straw, is much easier, without considering the environmental crisis and the human health risks they cause. On the other hand, such residues can be composted, used to generate biogas, or co-fired to generate energy (SWEET, 2014).

In the past, agricultural solid waste did not represent a problem in Egypt, until the use of synthesized materials that are not biodegradable (Zayani, 2010). Crop residues was re-used before in the farms to feed cattle, as fertilizers, or to be burned as a source of fuel. However, the use as a fuel has been decreased after the spread of propane/butane gas ovens and stoves. Moreover, the Ministry of Agriculture banned the storage of crop residues in order to avoid fires, and to fight diseases and pests. Therefore, farmers start to think of cheap disposal methods for their waste such as burning and random dumping, which decreased the utilization of agricultural waste from 100% to 40%. Table 3 shows the cultivated areas and generation of agricultural solid waste for major crops in Egypt (Zayani, 2010).

Table 3 - Cultivated areas and agricultural solid waste production for major crops (Zayani, 2010)

Crop	Cultivated area (feddan)	Solid waste generation (tons/feddan)	Total (tons)
Rice	1,507,634	2.1	3,015,000
Maize	1,657,799	1.9	3,150,000
Wheat	2,506,178	2.56	6,415,000
Cotton	535,090	1.6	856,144
Sugar cane	327,215	11.9	3,726,978
Total	6,206,701	-	17,163,122

1.6 Terminology of Alternative Fuels (AF)

A wide range of waste materials that have a definite calorific value can be used to produce Alternative Fuels (AF) after being processed. Alternative fuels can be defined as alternatives to conventional gasoline and diesel fuels. They are also derived from renewable sources and mostly have less negative impacts on the environment. As mentioned earlier,

alternative energy or fuels can be in a gaseous, liquid, or solid form, however, the focus of this research is solid alternative fuels from municipal, agricultural, and industrial waste that can be combusted to generate energy (Alternative Fuels, 2011).

There are many terms used to describe fuels derived from waste, however, the term “alternative fuel” is a generic term. Waste derived fuels contains residues from municipal solid waste, industrial waste, trade waste, sewage sludge, biomass waste and industrial hazardous waste. Refuse Derived Fuel (RDF), as a term in the English speaking countries, means the separated high calorific fraction of processed MSW, but there are also some other terms for MSW derived fuels like Processed Engineered Fuel (PEF), Paper and Plastic Fraction (PPF), and Packaging Derived Fuel (PDF). PPF and PEF are mainly composed of source separated, processed, dry combustible MSW (e.g. plastics and/or paper) that cannot be recycled because of the high contamination. However, it has a higher calorific value, lower ash content, and lower moisture content than RDF from mixed waste fractions. The main difference between PEF and RDF is that PEF is of higher quality and more homogeneous fuel than RDF. On the other hand, the term Recovered Fuel (REF) is usually used for “the processed residual of separate household collection of specific quality”. Other terms such as secondary fuel, substitute fuel, and substitute liquid fuel (SLF) mainly refers to industrial waste fractions like waste tires, waste oils, or processed solvents that should achieve consistent quality requirements for a particular process (Gendebien, et al., 2003).

1.7 Problem statement relating to Waste

Due to the depletion of fossil fuel resources, which has led to a great increase in its cost, it has become a necessity to find new alternatives. In addition to the different renewable energy resources such as solar, hydro, wind, and biofuels, WTE has been found to be an attractive solution for both lack of energy problems as well as the solid waste management

problems. In Egypt, a great portion of solid waste is thrown in open dump sites, which are unsafe, and do not include any preventive measures. The lack of enforcement of legislation, lack of environmental awareness, and poor management of solid wastes led to the aggravation of the solid waste problems in Egypt.

As a consequence for the abovementioned reasons, the utilization of alternative fuels that can be produced from non-recyclable wastes, in intensive-energy industries like the cement industry, has been deemed as a good solution for both the energy crisis as well as solid waste problems. Many incentives have promoted the use of wastes in cement kilns such as the huge area of the furnace, the high incineration temperature, the significant length of the kiln, and the alkaline environment inside the kiln (Ozkan & Banar, 2010). As a new alternative for energy, further research was needed to study the use of AF in different industries.

1.8 Objectives

The objective of this thesis is to investigate the use of solid waste in Egypt as alternative fuels, including: determining average calorific values of various municipal, agricultural, and industrial solid wastes in Egypt, examining the effect of using different binders on the average calorific value of biomass pellets, and conducting a relative comparison between the amount of pollutant emissions produced from the most promising wastes as mass per unit mass of the burned material. This comparison can be considered as an indicator to the real amount of emissions produced in the field, which would help in assessing the environmental impact of using those alternative fuels, which material should be used in terms of the calorific value and produced emissions, and making decision on mitigation measures that should be taken.

CHAPTER (2)

LITERATURE REVIEW

2.1 Introduction

Access to energy nowadays has become more expensive and more environmentally damaging. In Egypt, energy prices for industry have been increasing in the last few years, but this increase has not been drastic because prices remain governmentally regulated. The total consumption of energy in the industrial sector has increased from 17.5-million-ton oil equivalent (mtoe) in 2000/2001 to 27.2 mtoe in 2011/2012, which means an average annual growth rate of 4.1% during that period. Furthermore, the total final energy demand in the industrial sector is expected to increase from about 21 mtoe in 2008 to reach about 41-46 mtoe in 2030 according to the “Mediterranean Energy Perspective (MEP) – Case study of Egypt”. The largest energy demand goes to industry and electricity generation. Industry is divided into subsectors including iron and steel, fertilizers, and cement industry with the remaining industries categorized as “other” and which includes food, textile, etc (Logic Energy & Environics, 2014).

Cement industry constitutes one of the most energy-intensive industries. There are two main types of energy used in this industry, which are fuel and electricity. Electricity is used for exhaust fans and grinding mills, while fuel is used for firing the kilns, and drying and pre-heating raw materials. The main fuel for the cement industry is mainly provided by coal, natural gas, and fuel oil. Availability, cost, and environmental constraints are the key factors for choosing between those three fuels. Approximately, 3000-6000 MJ of energy is required per ton of clinker produced, and since natural gas is the main source of fuel in

Egypt's case. Its specific energy consumption is estimated with 100 m³ per ton of cement, which is about 5 kg of fuel oil per ton. Egypt's Energy Strategy for 2030 expects that demand for natural gas in the cement industry will increase from about 2.5 billion cubic meter (bcm) in 2008/2009 to be 14 bcm in 2029/2030 (Logic Energy & Environics, 2014).

Another problem that Egypt currently faces is the enormous amounts of solid waste that is clearly visible throughout the country and which cause various environmental and health hazards. Most experts agree that this waste can be a hidden treasure for the nation, if it is fully exploited. Indeed, solid waste can be reused, recycled, or even recovered as a source of energy instead of simply being disposed in dumpsters and landfills. However, Egypt suffers from serious problems with respect to its solid waste management (SWM) system and the problem worsened following the privatization of the SWM system which was taken over by international private sector in 2002. According to the Minister of State for Environmental Affairs, in a report issued in 2009, this move ultimately brought about the failure of Egypt's SWM system (Milik, 2010). Furthermore, it is predicted that the quantities of MSW will increase from about 21 million ton (MT) of waste in 2010 to more than 30 (MT) in 2025 (SWEEP, 2010). Additionally, the agricultural waste, as mentioned in Chapter 1, was estimated in 2012 at 30 million tons. Given the increasing levels of waste production and ongoing problems with waste management, a revolutionary SWM system is desperately needed and one which involves the collection, transportation, and disposal of waste. In order to minimize waste disposal in dumpsites and landfills, waste can be reused, recycled, or converted into energy. Considering the energy crisis, waste-to-energy seems to be the optimum solution for both problems: energy and waste disposal.

2.2 Utilization of Waste-to-Energy Technologies

Among those who have examined the waste-to-energy process, Munster and Lund (2010) performed an energy system analysis (ESA) of different waste-to-energy (WTE) technologies, while Psomopoulos, Bourka, and Themelis (2009) examined the benefits of waste-to-energy in terms of air emissions, energy production, and land saving.

Munster and Lund (2010) compared WTE technologies (as listed in Table 4), and identified a wide range of alternatives including chemical, thermo-chemical, and bio-chemical conversion processes. Those technologies include new waste incineration which is a technology using combined heat and power (CHP) waste incineration, co-combustion technology in which residual derived fuel (RDF) is co-combusted with coal in a coal fired power plant, and dedicated RDF technology where RDF is combusted in a dedicated CHP plant. Other technologies such as biogas CHP, biogas transport, syngas, biodiesel, and bioethanol are also included. Biogas CHP is a biogas that is produced by the anaerobic digestion of organic household waste that is used for CHP. Biogas transport is similar, but it is “upgraded and used for transport in natural gas vehicles”. Another technology is the syngas where municipal waste is liquidized and subjected to thermal gasification. Biodiesel is animal fat that is converted into biodiesel through a process called trans-esterification, while bioethanol is produced from paper, grass and straw which is fermented and used for transport, and through anaerobic digestion with biofuel and hydrogen used for CHP. Most of the technologies listed are used commercially. The authors stated that the energy system analysis was conducted using the EnergyPLAN model, which is a computer model designed for energy systems analysis. This model aims to aid in designing national or regional energy planning strategies based on technical and economic analyses of the consequences of implementing various energy systems and investments. The general inputs for the model are

renewable energy sources, demands, energy station capacities, costs, and optional different regulation strategies emphasizing import/export and excess electricity production, while the outputs are energy balances and resulting annual productions, fuel consumption, CO₂ emissions, import/export of electricity, and total costs including income from the exchange of electricity as shown in Figure 2. Three scenarios were analyzed, which are marginal change in the current energy system, marginal change in a 100% renewable energy system, and the use of full resource potential in the current energy system.

Table 4 - Summary of WTE technologies (Munster & Lund, 2010)

Technology	Description
New waste incineration	Combined heat and power (CHP) waste incineration with efficiencies of a new waste incineration plant. The technology is commercial. The waste fraction must be used continuously. The plant is placed in a larger city area with CHP
Co-combustion	Residual derived fuel (RDF) is co-combusted with coal in a coal-fired power plant. The technology is at full-scale demonstration stage. RDF can be stored. The plant is placed in a larger city area with CHP
Dedicated RDF	RDF is burnt in a dedicated CHP plant. The technology is commercial. The plant is placed in a large city area with CHP
Biogas CHP	Biogas from anaerobic digestion of organic household waste is used for CHP. The waste fraction must be used continuously. The technology is commercial. The plant is placed in a smaller town area with CHP

Biogas transport	Biogas from anaerobic digestion of organic household waste is upgraded and used for transport in natural gas vehicles. The technology is commercial. The plant is placed in a smaller town area with CHP
Syngas	Municipal waste is liquidized and undergoes thermal gasification. The resulting syngas can be converted to bio-petrol or used for CHP. The technology is at developmental stage. The waste fraction must be used continuously. The plant is placed in a larger city area with CHP
Biodiesel	Animal fat, formerly used for industrial heat production, is converted to biodiesel in a trans-esterification process. The animal fat can be stored. The technology is commercial. The plant is placed in a smaller town area with CHP
Bioethanol	Straw, grass, and paper waste first undergoes pre-treatment and hydrolysis. Secondly, Bioethanol is produced for transport through fermentation and thirdly biogas is produced through anaerobic digestion along with biofuel and hydrogen and used for CHP. The waste fractions can be stored. The technology is at developmental stage. The plant is placed in a smaller town area with CHP

From this analysis, it was shown that biogas and syngas plants are notable alternatives to waste incineration. The use of organic waste in manure-based biogas production reduces CO₂ cost in the energy system, so it is considered as a cheaper solution

than incineration and one that also provides CO₂ reduction. The largest CO₂ reduction was obtained when biogas was used for transport, while the least CO₂ reduction cost was provided by biogas for combined heat and power (CHP). Moreover, it was found that biogas production is a feasible solution that provides the cheapest biomass reduction in a future 100% renewable energy system. Other studies also concluded that biogas can be as good as or an even a better alternative to incineration depending on the design of the system. According to Munster & Lund, it was concluded that biogas production does decrease CO₂ emissions in the current energy system but only if an increased anaerobic digestion of manure takes place during the process. Syngas plants gives the lowest CO₂ reduction cost in the current energy system as long as there is no coal; total CO₂ emissions increase when co-gasified with coal. However, during this study, it was found that plants that co-gasify waste with other resources were still at the developmental stage, and those which gasify waste separately were far from becoming a commercial technology and required a great deal more research. Syngas gasified with waste only provides a reduction in the biomass cost, which is only slightly higher than that of incineration, but still less than the expected biomass cost. However, these values may get higher if several technologies are combined because of the usage of different waste fractions. Changes in waste prices, efficiencies and investment costs dramatically influence selection, especially in case of the waste resources that do not have a well-developed market. Also, the highest uncertainty for investment costs and efficiencies were apparent among technologies that were still at the development stage like Syngas and Bioethanol. The authors found that it is possible to use waste for producing transport fuels from the perspective of an energy system. One of the best solutions is to sort out RDF and co-combust it with coal or burn it in a dedicated RDF plant to improve the electric efficiency and the flexibility of the energy system. If the investment in new plants is considered, dedicated RDF plants gives more CO₂ reduction and less CO₂ reduction cost than new

incineration, but they can handle only 19% of the waste that is currently incinerated. Co-combustion and RDF alternatives has been proven to be interesting in the short term (Munster & Lund, 2010).

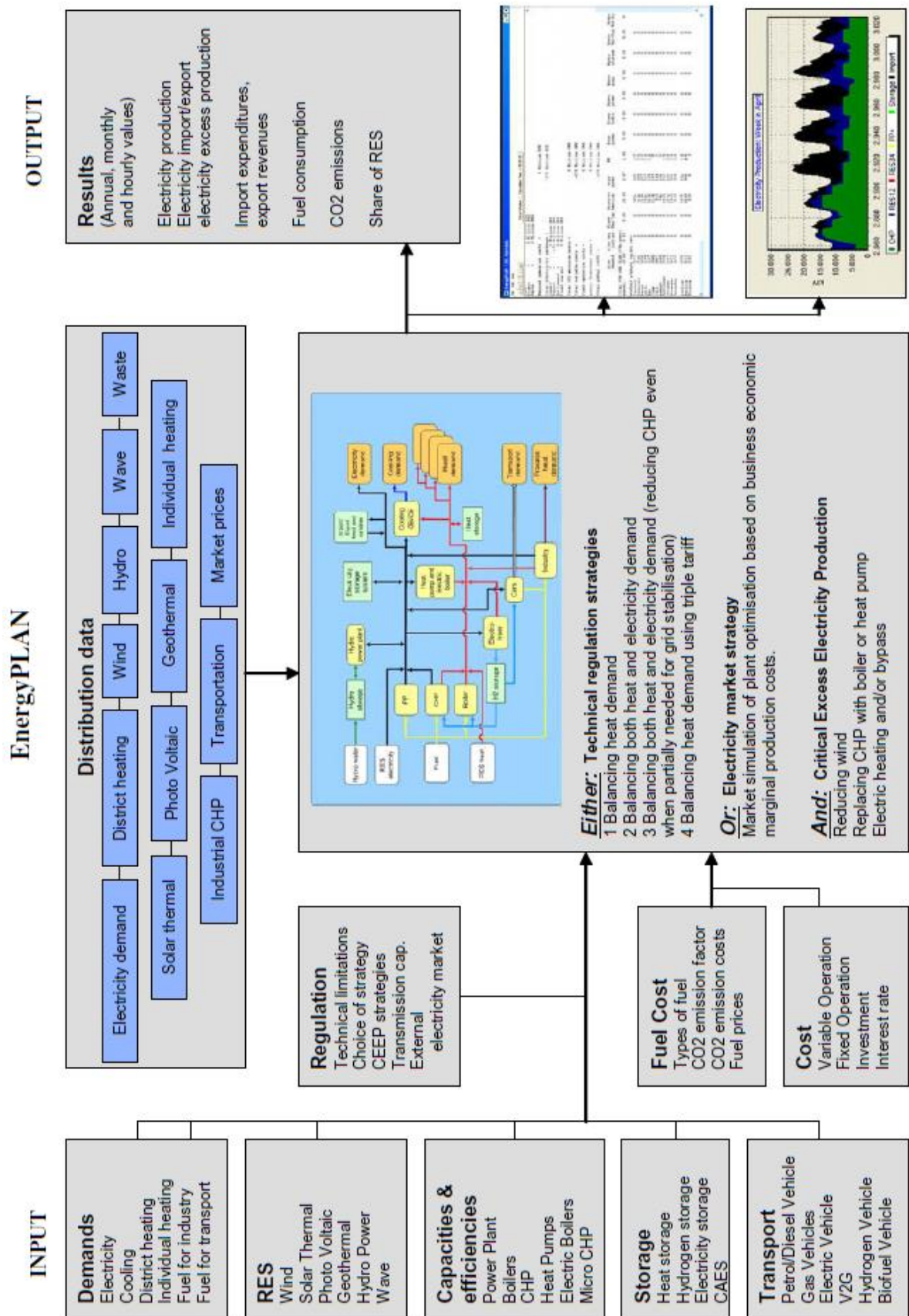


Figure 2 - Schematic overview of the EnergyPLAN model (Munster & Lund, 2010)

In another study, Psomopoulos, Bourka, and Themelis (2009) focused on the current status and benefits of waste-to-energy (WTE) regarding dioxin, mercury, and greenhouse gases (GHG) emissions, energy production, and land saving based on the experience of operating facilities in U.S. About 7.4 % of MSW in U.S. in 2004 was used for combustion and the generation of electricity. The authors found that on average, the combustion of 1 metric ton of MSW in a modern WTE power plant can avoid the mining of ¼ ton of high quality coal or one barrel of imported oil because it generates about 600 kWh electricity. For non-recyclable wastes, WTE is considered the only alternative to landfilling, which generates carbon dioxide and methane, a greenhouse gas. At least 25% of the methane gas emitted from decomposing trash escapes into the atmosphere before a landfill is capped and this is even in the modern sanitary landfills. According to the authors, several studies concluded that WTE decreases greenhouse gases emissions by approximately 26 million tons of carbon dioxide, taking into consideration the generated electricity and the avoided methane emissions. Table 5 shows a comparison between air emissions from WTE power plants that used MSW as fuel, and fossil fuel power plants. Moreover, WTE plants currently represent less than 1% of the U.S. emissions of dioxins and mercury. Table 6 shows a comparison between the average emissions of 87 U.S. WTE facilities according to Environment Protection Agency (EPA) standard requirements. The recorded average values showed that all emissions including dioxins/furan, particulate matter, sulfur dioxide, nitrogen oxides, hydrogen chloride, mercury, cadmium, lead, and carbon monoxide were within the range of U.S. EPA standards. As for the nitrogen oxides NO_x, the total emission from WTE is about 0.22% of the total U.S. NO_x emissions, which is very small when compared with coal-fired power plants that contribute with 19.5% of U.S. NO_x emissions. In addition, waste as a fuel is deemed as a source of renewable energy, categorized as a type of biomass, which includes any plant or animal-derived organic matter that is available on a

renewable basis such as trees, agricultural food, animal wastes, agricultural crop wastes and residues, municipal wastes and wood wastes and residues. In 2004, the U.S. generated a net of 13.5×10^9 kWh of electricity from WTE facilities, which is greater than all other renewable sources of energy, except for geothermal power and hydroelectric power. WTE plants save land as they need significantly smaller areas of land than for landfilling for the same amount of waste. Also, WTE plants can last for over 30 years if maintained properly and do not require more land afterwards, unless they are expanded to process more waste (Psomopoulos, Bourka, & Themelis, 2009).

Table 5 - Waste-to-energy and fossil fuel power plants – comparison of air emissions (Psomopoulos, Bourka, & Themelis, 2009)

Fuel	Air emissions (kg/MW h)		
	Carbon dioxide (CO ₂)	Sulphur dioxide (SO ₂)	Nitrogen oxides
MSW	379.66	0.36	2.45
Coal	1020.13	5.90	2.72
Oil	758.41	5.44	1.81
Natural gas	514.83	0.04	0.77

Table 6 - Average emissions of 87 U.S. WTE facilities (Psomopoulos, Bourka, & Themelis, 2009)

Pollutant	Average emission	U.S. EPA standard	Average emission (% of U.S. EPA standard)	Unit
Dioxins/furan, TEQ basis	0.05	0.26	19.2%	ng/dscm
Particulate matter	4	24	16.7%	mg/dscm
Sulfur dioxide	6	30	20%	ppmv
Nitrogen oxides	170	180	94.4%	ppmv
Hydrogen chloride	10	25	40%	ppmv
Mercury	0.01	0.08	12.5%	mg/dscm
Cadmium	0.001	0.020	5%	mg/dscm
Lead	0.02	0.20	10%	mg/dscm
Carbon monoxide	33	100	33.3%	ppmv

dscm: dry standard cubic meter of stack gas

2.3 Alternative Fuels (AF) from solid waste

Several studies have been conducted to investigate the use of potential wastes as a renewable energy source to solve both energy and waste problems:

2.3.1 Refuse derived fuel (RDF)

Attili (1991) identified three main methods for burning municipal solid waste, which are direct combustion, conversion of MSW into liquid or gaseous fuel by means of pyrolysis, biodegradation, or hydrogenation, and burning the combustible portion of MSW (RDF) after separating the incombustible portion. Attili also stated that one ton of RDF can produce the

energy equivalent of one barrel of oil. There are seven types of RDF, which are shown in Table 7, including (RDF-1), which is the discarded waste used as it is without undergoing any processing, (RDF-2) is the waste that has been processed into coarse particles and which may not include ferrous metal separation, (RDF-3) is processed to remove glass, metals, and other inorganic materials, (RDF-4) is processed into a powder form, (RDF-5, or d-RDF) is densified into a form of pellets or briquettes, (RDF-6) is processed into liquid form, while (RDF-7) is processed into gaseous form. The disadvantages of (RDF-1) are that it is hard to handle, usually burned in suspension, and that much of it remains unburned and thus causes problems when handling the ash. There are some benefits for using any type of RDF over raw refuse, including that it is easier to store RDF when it has been properly processed, combustion is possible in existing boilers, gasifiers, fluidized bed combustors, and cement and brick kilns, as well as the fact that it is easy to transport from one location to another, and can be burned as a supplemental fuel with other fuels such as coal or wood, it is also more homogeneous, and can be used as a feedstock for anaerobic digesters to produce methane gas (Attili, 1991).

Table 7 - Types of Refuse Derived Fuel (RDF) (Attili, 1991)

RDF-1	Waste used as fuel in as-discarded form
RDF-2	Waste processed to coarse particle size with or without ferrous metal separation
RDF-3	Shredded fuel derived from MSW that has been processed to remove metals, glass, and other inorganic materials (95 wt% passes 50-mm square mesh)
RDF-4	Combustible waste processed into powder form (95 wt% passes 10 mesh)
RDF-5	Combustible waste densified (compressed) into a form of pellets, slugs, cubits, or briquettes (d-RDF)
RDF-6	Combustible waste processed into liquid fuel
RDF-7	Combustible waste processed into gaseous fuel

In another study conducted by Dong and Lee (2009), the authors evaluated the energy potential of the RDF obtained from the use of combustible solid waste as a fuel in Ulsan, which is the largest industrial city of Korea. Combustible solid wastes including wastepaper, rubber, synthetic resins, wood, plastic, and industrial sludge were used as RDF resources. The amount of wastes that can be used to produce RDF was about 635,552 tonnes/yr out of 3.3 million tonnes of solid wastes generated in the city. The produced RDF was divided into three types: 116,803 tonnes/yr of RDF-MS (RDF from municipal solid waste), 146,621 tonnes/yr of RDF-IMC (RDF from industrial, municipal, and construction wastes), and 372, 848 tonnes/yr of RDF-IS (RDF from industrial sludge). The total obtained energy value from RDF was more than $9,375,930 \times 10^6$ kJ/yr, about 25.6%

of RDF-MS, 43.5% of RDF-IMC, and 30.9% of RDF-IS. The energy values obtained were $4,082,488 \times 10^6$ kJ /yr from RDF-IMC, $2,895,772 \times 10^6$ kJ /yr from RDF-IS, and $2,397,670 \times 10^6$ kJ /yr from RDF-MS, as shown in Table 8. The greatest total energy values were obtained from RDF-IMC followed by RDF-IS, then RDF-MS. According to the economic analysis undertaken by the authors, the ratio between the profit of RDF selling to RDF production costs varies based on the different types of RDF. The ratios of RDF-MS, RDF-IMC, and RDF-IS are 1.21, 0.57, and 0.27 respectively. RDF-IS has the lowest ratio and lower energy values. The ratio of RDF-MS is >1 that represents greater benefits from RDF resources than the expenses for the utilization of RDF (Dong & Lee, 2009).

Table 8 - Total energy obtained from combustion of the RDF resources in the industrial city (Dong & Lee, 2009)

RDF type	Waste type	Heating value (kJ/kg)	Average energy value (kJ/kg)	Energy (x10 ⁶ kJ/yr)	Energy value (%)	
RDF-MS	General MSW	20656	20656	2,397,670	100.0	25.6
RDF-IMC	-Industrial MSW	24920	27844.5	68,233	1.7	43.5
	-Construction waste	26539		468,821	11.5	
	-Industrial process waste	28091		3,545,430	86.8	
	-Subtotal			4,082,488	100.0	

RDF-IS	-Wastewater treatment sludge	7531	7766	2,676,317	92.4	30.9
	-Process sludge	12552		219,455	7.6	
	Subtotal			2,895,772	100.0	
Total			14753	9,375,930		100.0

2.3.2 Plastics and tires

Among those studies, Piasecki, Rainey, and Fletcher (1998) examined the need to incinerate plastics because of the increasing demand for using plastics, which then takes hundreds of years to degrade after disposal, and it occupies landfills for so long. Therefore, plastic waste should be recycled or burned in a WTE plant instead of being buried. However, recycling is found to be more costly than landfilling and incineration. Due to the abovementioned reasons, burning plastics seemed to be more preferable since plastics are considered relatively clean, economical, and reliable source of energy. One of the reasons behind making waste combustion more attractive is the need for reducing greenhouse gases generated by fossil fuels. The authors explained that if a plastic bottle is buried, it will never be recovered. However, if the same bottle is recycled, the materials used in manufacturing this bottle will be partially recovered. In the third case, if the same bottle is used as a WTE source, it will be recovered as a portion of the initial energy invested in producing this bottle in the form of electricity, heat, or steam, which is more significant due to the climate change. On the other hand, plastic combustion releases some compounds such as acid gases, polyvinyl chloride, carbon dioxide, dioxins, and heavy metals like lead and cadmium. All

those compounds are harmful to humans, the atmosphere, as well as the environment. However, the authors stated that policy makers should examine each of those concerns while considering burning plastic waste. They also mentioned that among all wastes, plastics has released the highest energy per unit of weight. Therefore, the authors argued that mitigation and air-pollution control technologies can be used to reduce emissions to acceptable levels and make WTE an acceptable waste management strategy. The authors presented a study conducted by Fredrick E. Mark in 1994 in a commercial WTE facility in Wurzburg, Germany, for the Association of Plastics Manufacturers in Europe. In this study, Mark studied the emission profile of waste, where plastics ranged from 10% of the total weight, 17.5% in the medium case, to high composition level of about 25%. The study was designed to examine the impacts of burning plastics in a real operating environment. As plastic was added above the base percentage of 10%, the total amount of solid waste fed into the incinerator was decreased. The tested plastic materials included polystyrene, polyethylene terephthalate, polyethylene, and polyvinyl chloride. The level of hydrochloric acid emissions, dioxins, and furans did not change in the three cases. The results showed that treating the flue-gases with pollution controlling lime and activated carbon, reduced stack-gas concentrations of dioxins. Mark noted that the measured dioxin levels in his study were in the acceptable range of the European solid waste combustion industry. He also concluded that the furnace was well run and designed, and that pollution control equipment as well as controlled combustion easily decreased hydrochloric acid and avoided further formation of dioxins, even when plastics percentage in the total waste composition increased, as shown in Table 9. He also stated advantages of WTE, among which is that WTE plants generally produces electricity and selling it to the electric utilities for more competitive prices than those offered by power plants that generate energy by fossil fuels or nuclear power plants (Piasecki, Rainey, & Fletcher, 1998).

Table 9 - Emission profile of burned waste in a modern WTE facility that incorporates pollution-control mechanisms (Piasecki, Rainey, & Fletcher, 1998)

	Base Case (10%)	Medium polymer (17.5%)	High polymer (25%)
Hydrochloric acid (mg/m ³)	23.5	22.4	21.4
Dioxin toxic equivalents (mg/m ³)	0.021	0.014	0.013
Carbon monoxide (mg/m ³)	19	18	7
Sulfur dioxide (mg/m ³)	19	9	<5
Nitrogen oxides (mg/m ³)	405	385	410
Dust (mg/m ³)	2.4	<2	2.4
Furnace temperature (°C)	890	892	894

Martinez, Puy, Murillo, Garcia, Navarro, and Mastral (2013) stated the potential of using tires as an alternative fuel in their review as tires provide higher calorific value than coal. Waste tires are considered as bulky and non-biodegradable materials, that causes waste management problem due to the fact that approximately 1.4 billion new tires are sold annually worldwide and meanwhile similar amount falls under the category of end-of-life tires. Also, as estimated, one car tire per person is discarded every year in the developed world, therefore about one billion of waste tires are disposed annually all over the world.

About 4 billion waste tires are accumulated in stockpiles and landfills leading to an environmental and economic problem. The tire lifetime in landfills ranges between 80 and 100 years approximately. Another concern with inappropriate disposal of tires is that it promotes the growth of insects and pests, imposing high risk of fire, and uncontrolled emissions of harmful compounds into the environment. Regarding emissions, the global warming and harmful pollutants resulted from fossil fuels such as SO₂, NO_x, and VOCs and others, are considered as a main reason behind the need for alternative fuels in general. The authors stated that waste tires have been widely used as alternative fuels in many applications such as power plants, cement kilns, tire manufacturing facilities, and pulp and paper production. However, many studies demonstrated that cement kilns can be the major route for using tires as a supplemental fuel due to the longer residence time and higher temperatures in cement kilns that helps in the tire transformation, especially carbon black combustion. Also, the iron contained in the tire steel beads and belts can be utilized in the cement production process without affecting the cement quality. It was also found that tires can be used as direct fuel in bubbling fluidized bed reactors (BFBR) as gasifiers and combustors and hence it is feasible to use tire derived fuel (TDF) in thermal power plants as secondary fuel in order to reduce the use of coal and NO_x emissions. One of the benefits for using waste tires for energy recovery in cement kilns is that it does not require major modifications in the layout and operation of the plant (Martinez, et al., 2013).

2.3.3 Biomass

Biomass can also be used as alternative fuels due to its abundance and reasonable calorific values. Many studies have been carried out to examine the conversion of biomass waste into energy.

According to Kilicaslan, Sarac, Ozdemir, and Ermis (1999), bagasse can be used as a fuel for boilers instead of fossil fuels. About 255 kg of bagasse is produced from one ton of cane, and the gross calorific value of bagasse is 17632 kJ/kg (Kilicaslan, Sarac, Ozdemir, & Ermis, 1999). Another research by Dellepiane, Bosio, and Arato (2003) recommended the use of bagasse and barbojo for the production of electric energy. This study took place in Peru, where large quantities of sugarcane waste are produced, but not fully exploited for energy purposes. Bagasse is the fiber of cane produced by milling and pressing the cane in sugar mills, while barbojo is the tops and leaves left in the field after harvesting. Bagasse is not widely used in the energy sector, however, it is used with fossil fuels to produce steam in sugar mills. The generated steam is used partially in the cane milling and the rest in the mill's turbines to provide the electrical energy needed for the plant. However, the present technologies used in the sugar mills resulted in low energy efficiencies and emissions from the boiler pollutant are released into the atmosphere. Therefore, this study investigated the feasibility of generating electrical power using a molten carbonate fuel cells (MCFC) system fed by biogas from sugarcane residues. Figure 3 demonstrates the entire process of converting bagasse and barbojo into electricity. First, bagasse and barbojo were preheated, then they enter a fluidized bed gasifier indirectly fired, where steam injected to boost biomass gasification. Afterwards, a clean-up process took place to prevent impurities disposition that might plug pipes and tubes, and finally the gas enters the MCFC section. The results obtained from this research showed that Peru can get several benefits from applying this process to bagasse and barbojo. Also, this innovative way can generate significantly higher amounts of power than the actual power produced by sugar mill boilers using bagasse and fossil fuels. Additionally, boiler emissions as well as emissions from barbojo and bagasse burning could be reduced. Thus,

such quantitative and qualitative energy improvements can be applied in countries that want to invest in sugarcane wastes (Dellepiane, Bosio, & Arato, 2003).

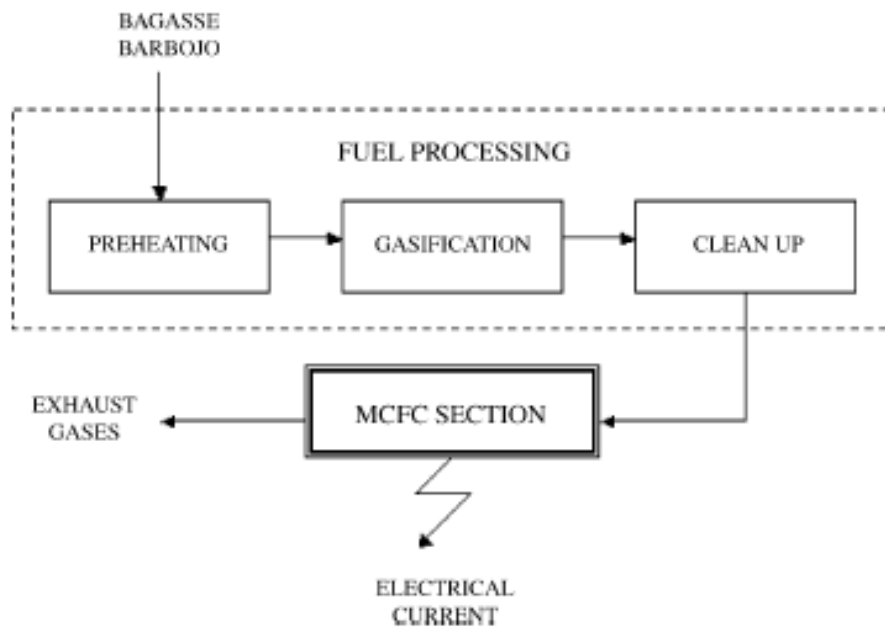


Figure 3 - The entire process from sugarcane waste to electricity (Dellepiane, Bosio, & Arato, 2003)

Another study conducted by Oladeji (2010) studied the properties of fuel produced from rice husk and corn cobs residues. The author examined the characteristics of briquettes made from both rice husk and corn cobs residues to find out which is more efficient to be used as fuel. This study was conducted in Nigeria, where cooking gas, and kerosene are costly and firewood causes environmental problem. Therefore, alternative sources of energy need to be used, and from here the need to improve the use of agro wastes has come out. Rice husk and corn cobs are produced annually in large quantities in Nigeria, and they are left to decompose or burned like other wastes. However, they have a high potential to generate heat for industrial and domestic cottage applications. In this study, the author used briquetting technology for densification in order to facilitate transportation, storing, and handling of rice husk and corn cobs residues. The investigated characteristics of corn cobs and rice husk briquettes were density, moisture content, ash content, volatile matter, and

heating value. The results of this study showed that corn cobs briquettes have better fuel characteristics than rice husk with a moisture content of 13.47% and 12.67%, density of 650 and 524 kg/m³, ash content of 1.40 and 18.60 %, volatile matter of 86.53 and 67.98%, and heating value of 20890 and 13389 kJ/kg, respectively, as shown in Table 10. According to the author, the values of ash content and volatile matter were acceptable, however, corn cobs briquettes were better because they had lower ash content and higher volatile matter percentage (Oladeji, 2010).

Table 10 - Characteristics of rice husk and corn cobs briquettes (Oladeji, 2010)

Parameter	Briquettes	
	Rice Husk	Corn Cobs
Moisture content (%)	12.67	13.47
Heating value (kJ/kg)	13389	20890
Density (kg/m ³)	524	650
Ash content (%)	18.60	1.40
Volatile matter (%)	67.98	86.53

2.4 Pellets - Characteristics

Biomass bales are both difficult to transport over long distances and difficult to store because they are so bulky. Thus, it is easier to densify biomass by pelletizing in order to increase the bulk density. Furthermore, the uniform shape and size of the pellets make it easier to handle, and so reduce transportation costs, and improve storability. The physical properties of pellets include particle density, bulk density, durability, moisture content and other properties (Theerarattananoon, et al., 2011).

Theerarattananoon (2011) studied the physical properties of sorghum stalk, corn stover, big bluestem, and wheat straw, putting into consideration the effect of moisture content on bulk density and the durability of pellets, as well as the effect of grain size on the same properties. It was shown that biomass pelletizing did improve the bulk density significantly. The results showed that the bulk density of pelletized big bluestem, corn stover, wheat straw, and sorghum stalk was within range of 536-708 kg/m³, which means 6-10 times higher than the bulk density before pelletizing. The bulk density of the wheat straw pellets was the highest, while the bulk density of the sorghum stalk pellets was the lowest. Increasing the moisture level decreased the bulk density of the pellets as stated in this study and previous studies from the literature because the volume of pellets increased when they absorbed more moisture. The author also found that the effect of moisture content on the pellets' durability made from wheat straw, corn stover, and big bluestem was similar to its effect on the bulk density. As reported in many studies, densification of biomass with the increase in moisture content increased its durability and strength until reaching an optimum. The defined optimum moisture content for biomass ranges within 8-12%. The maximum durability of corn stover, and wheat straw pellets were about 96.8% and it did not change within range of 9-14% moisture content (dry basis). However, durability decreased when the moisture content increased beyond 14% (dry basis). The same trend was applied for big bluestem pellets, but with maximum durability 96.8% at 9-11% moisture content (dry basis), and it tended to decrease beyond 11% (dry basis). The author explained that the binding forces of the water molecules were probably the reason behind the initial increase in durability with an increase in moisture because they strengthened the bonds between individual particles in the pellets. However, further increases in moisture caused disintegration and swelling of pellets due to the absence of the capillary force that maintains the pellet structure. Thus, the pellets racked and got more susceptible to breakage. On the

other hand, the use of a larger grain size was found to increase the bulk density and durability of biomass pellets, but not in significant levels. The use of larger size of 6.5 mm instead of 3.2 mm increased the durability of wheat straw, big bluestem, and sorghum stalk pellets to 98.3, 97.6, and 93.5% instead of 97.4, 96.9, and 92.2%, respectively. Using the same screen size of 3.2 mm and 6.5 mm, the bulk density did not change significantly to reach 649.2, 618.0, 624.6, and 478.6 kg/m³ instead of 554.1, 601.9, 597.9, and 434.0 kg/m³ for wheat straw, big bluestem, corn stover, and sorghum stalk, respectively (Theerarattananoon, et al., 2011).

Attili (1991) evaluated the use of 150 binders. His preliminary evaluation eliminated about half of the binders for different reasons, such as the cost, effectiveness as a binder, and environmental acceptability. The binder candidates included oil, kiln dust, glue, and wax. The candidates were evaluated based on laboratory and environmental studies. The laboratory studies included binder British thermal units (BTU) content, ash content, pellet's water absorbability, pellet's durability, and pellet's weatherability. As for the environmental aspect, the author evaluated the toxicity as well as the potential of harmful emissions of the binder. The author stated that calcium hydroxide Ca(OH)₂ was the best binder to be added for densification among all the investigated binders. The pellets were produced by two suppliers, one with a bulk density of 400.5 - 432.5 kg/m³, and the other with a density of 640.7 - 720.8 kg/m³. It was found that as the pellets' bulk density increases, the mechanical durability increases. This binder can delay the biological and chemical degradation for long time. The focus of this study is to solve the environmental problems toxic trace metals emissions. The most concerned toxic heavy metals are Ba, Cd, Cr, Hg, Cu, Be, As, Ni, Pb, Se, Sb, Tl, and Zn. It was found that adding binder to RDF pellets reduces some trace metal emissions as well as other harmful emissions like dioxins, furans, polychlorinated biphenyl

(PCBs), and polycyclic aromatic hydrocarbons (PAHs), when the binder densified RDF (bdRDF) is co-fired with sulfur-rich coal with 10%, 20%, 30% RDF. The increase of the binder content caused a reduction in the trace elements (Attili, 1991).

Said, Abdel daiem, Maraver, and Zamorano (2015) carried out a study that investigated densification parameters that could affect the properties of rice straw pellets. Rice straw is considered as one of the most important agricultural residues that can be used as a renewable form of energy because it has a great energy potential and it is a major by-product in many countries. The authors stated that the annual production of rice straw is approximately 731 million tons with 20.9, 667.6, 3.9, 37.2, and 1.7 million tons in Africa, Asia, Europe, America, and Oceania respectively. Mainly, open burning in the field is used widely for rice straw disposal, however, rice straw can be used as a source of energy instead. The use of rice straw as an alternative fuel would help in substituting fossil fuels, reducing greenhouse gas emissions, and lessening pollution problems resulted from open burning. There are many techniques to convert rice straw into energy such as direct combustion, pyrolysis, gasification, and anaerobic digestion. However, direct combustion provides relatively high energy conversion efficiency, but it involves operating problems like sintering formation and high ash content. Yet, those problems can be eliminated by chemical and biological pretreatment and rinsing rice straw. Another problem with utilization of rice straw for as a source of energy is the cost, collection, transportation, and handling due to its low density. Nevertheless, pelletizing can increase the biomass bulk density from 40-200 kg/m³ to 600-800 kg/m³ as well as facilitating storage and handling. In order to densify biomass, a binding agent is needed to form a bridge and chemical reaction to strengthen inter-particle bonding. Generally, the selection of a binder depends on its cost and environmental impacts. According to Ewida et al. (Ewida, El-Salmawy, Atta, & Mahmoud,

2006) as mentioned in this study, starch was the best binder among five binding agents, which are sodium silicates, starch, latex, molasses, and phenol-formaldehyde, in terms of strength and combustion characteristics. In this study, the authors examined the influence of changing starch percentage as a binder (0, 1, and 2%), moisture content of the feeding material (M_f) (12, 15, and 17%), and the operating temperature (below and over 50°C) on the pellet properties including hardness, single pellet and bulk density, durability, and moisture content of pellets (M_p). The obtained results were evaluated according to the European Standard for non-woody biomass pellets as shown in Table 11. Based on the analysis of results from this study, it was found that hardness, bulk density and durability are the most affected properties by M_f and starch ratio, while M_f had a significant impact on M_p . However, M_p did not comply with the standard ranges. Regarding hardness and pellet density, they were not addressed by the norm, but the obtained results were close to the ones recommended by earlier studies. The maximum pellet quality was obtained at 17% M_f , 2% starch, and temperature less than 50°C, providing hardness of 21 kgf, durability of 99.31%, pellet density of 1260 kg/m³, bulk density of 740 kg/m³, and M_p of 14.80% (Said, Abdel daïem, Maraver, & Zamorano, 2015).

Table 11 - Parameters and guidelines in UNE-EN ISO17225-6, including specifications for non-woody pellets (Said, Abdel daïem, Maraver, & Zamorano, 2015)

Parameter	Guideline
Moisture content (%)	≤ 10.00
Durability (%)	≥ 97.50
Bulk density (kg/m ³)	≥ 600
Additive (%)	Declare type and quantity

Telmo and Lousada (2011) investigated the heating values of wood pellets from different species. Due to the great areas of forest in Portugal, where this study was conducted, large amounts of residues are produced from forests including wood waste. Biomass can provide a sustainable and cost effective supply of energy in addition to aiding in reducing GHG emissions. According to the authors, the most important property to categorize a material as combustible is the calorific value. A bomb calorimeter was used to measure the calorific values of twelve wood species in Portugal and five wood tropical residues from industry. The results obtained from this study showed that the calorific values of pellets from different wood species differ. Softwoods had calorific values range between 19660 and 20360 kJ/kg, while calorific values of hardwoods were ranging between 17632 and 20809 kJ/kg (Telmo & Lousada, 2011).

2.5 Pellets - Limits and Standards

There are also several studies that discussed limits and standards for manufacturing biomass pellets. Karkania et al. (2012) stated that some countries, which have well-developed pellet industries, such as Austria, Germany, and Sweden, have developed their own standards for pellets, while other countries that are major producing regions, like Denmark and Finland, have chosen to follow a common European Standard (CEN/TS 14961) for solid biofuels. A technical committee 335 from the European Committee for Standardization (CEN) is responsible for developing this common pellet standard. This European Standard identifies which parameters must be tested, and which are optional. Also, it determines the limit values and ranges for each characteristic such as unit density, bulk density, water content, calorific value, ash content, sulfur, chlorine, and nitrogen (Karkania, Fanara, & Zabaniotou, 2012).

In Germany, there are pellet fuel standards called DIN-52731/DIN*plus*, while in Austria there are Ö-Norms M-7135. Table 12 shows the specified limits for DINplus, DIN51731, and Ö-Norm M-7135 (Verma, Bram, & De Ruyck, 2009).

Table 12 - Quality requirements of pellet fuel as per the respective regulation/quality standard (Verma, Bram, & De Ruyck, 2009)

Parameter	DINplus	DIN-51731	Ö-Norm M-7135
Diameter (mm)	4-10	4-10	4-10
Length (mm)	5xD ^a	≤ 50	5xD
Density (kg/m ³)	≥1.12	≥1-1.4	≥1.12
Humidity (% wt)	≤ 10	≤ 12	≤ 10
Ash (% wt)	≤ 0.5	≤ 1.5	≤ 0.5
Heating value (MJ/kg)	≤ 18	15.5-19.5	≥18
Sulphur content (% wt)	≤ 0.04	≤ 0.08	≤ 0.04
Nitrogen content (% wt)	≤ 0.30	≤0.30	≤ 0.30
Chlorine content (% wt)	≤ 0.02	≤ 0.03	≤ 0.02
Abrasian/fine content (% wt)	≤ 2.3	-	≤ 2
Mechanical durability (% wt)	≥ 97.5	-	≥ 97.5
Binding agent/additives (% wt)	< 2	-	< 2

a No more than 20% of the pellet may be longer than 7.5 x diameter

Another standard is the PFI pellet fuel standards. PFI is the acronym for the Pellet Fuels Institute, which is a non-profit trade association that serves the North American densified fuels Industry. These standards originally started in 1995, and were redeveloped

in 2005. The most recent updated standards were released in 2008, as shown in Table 13 (Hedrick, 2011).

Table 13 - PFI pellet fuel standards (Hedrick, 2011)

Fuel Properties	PFI Premium	PFI Standard	PFI Utility
Normative Information – Mandatory			
Diameter (inches)	0.230-0.285	0.230-0.285	0.230-0.285
Diameter (mm)	5.84-7.25	5.84-7.25	5.84-7.25
Bulk Density (lb/ft ³)	40.0-46.0	38.0-46.0	38.0-46.0
Pellet Durability Index	≥ 96.5	≥ 95.0	≥ 95.0
Fines % (at the mill gate)	≤ 0.5	≤ 1.0	≤ 1.0
Inorganic Ash %	≤ 1.0	≤ 2.0	≤ 6.0
Moisture %	≤ 8.0	≤ 10.0	≤ 10.0
Chloride ppm	≤ 300	≤ 300	≤ 300
Heating Value	NA	NA	NA
Informative Only – Not Mandatory			
Ash fusion	NA	NA	NA

2.6 Combustion of Alternative Fuels (AF)

There are many studies conducted to examine combustion and emissions of alternative fuels. Among those studies, Okasha (2007) examined the staged combustion of rice straw in a fluidized bed. Agricultural wastes are still considered as a huge environmental problem due to the fact that many of them are subjected to open burning without energy recovery, especially rice straw as explained in previous sections. Rice straw causes the most

serious problem because it is available in large quantities and cannot be handled or transported easily, so it is easier to be disposed of by direct open burning in fields. However, utilization of biomass in energy generation is a promising solution to substitute fossil fuels, and solve the waste disposal problem. Fluidized bed combustion (FBC) is commonly used for combustion of different biomass fuels. FBC has advantages over other combustion technologies due to the easy and efficient control of SO_x and NO_x emissions as well as the possibility of using various fuels. FBC is also an economically effective technology because of the emissions reduction in the FBC furnace without the need for supplementary flue gas cleaning devices. In this study, an atmospheric bubbling FBC was used with secondary air introduced in the freeboard. Rice straw was fed in cylindrical pellets form. It was found that staged combustion is an efficient technique to decrease NO_x emissions, especially at higher temperatures, as it was reduced by 50% at 850°C when 30% of fed air is introduced as secondary air. Combustion efficiency improved when increasing the ratio of secondary air until a maximum ratio because of the reduction in fixed carbon loss. However, further increase in the secondary air ratio reduced combustion efficiency due to the increase in entrained fixed carbon and exhausted carbon monoxide. Higher operating temperatures resulted in expanding the range of secondary air ratio, over which combustion efficiency increased. Furthermore, air staging had a slight effect on SO_2 as SO_2 reduced in the lower range of the secondary air ratio, and slightly increased when increasing bed temperature behind 800°C (Okasha, 2007).

Another study by Villeneuve, Palacios, Savoie, and Godbout (2012) included a review of regulations and standards for emissions from biomass combustion. Biomass is composed mainly of Carbon (C), Nitrogen (N), Hydrogen (H), Sulphur (S), Chlorine (Cl), and Oxygen (O). In addition, other elements are present in less proportion like Sodium (Na),

Potassium (K), Calcium (Ca), Magnesium (Mg), Phosphorous (P), and heavy metals such as Chromium (Cr), Copper (Cu), Arsenic (As), Cadmium (Cd), Mercury (Hg), Lead (Pb), Nickel (Ni), and Zinc (Zn). The authors explained ideal combustion as the full oxidation of all fuel components. In case of ideal combustion, it is assumed that the basic elements in biomass, which are (C, H, N, S, and O), would be available in the form of (CO_2 , H_2O , N_2 , SO_2 , and O_2) in the flue gas. Emissions from biomass combustion are affected by factors other than the chemical composition of biomass such as the type of combustion equipment, emission reduction measures, biomass physical properties including moisture content, porosity, density, size, and active surface area. There are two general categories for emissions according to the reaction type, which are emissions from complete combustion such as CO_2 , NO_x , SO_x , HCl, particulate matters (PM), and heavy metals, and emissions from incomplete combustion resulted from lack of available O_2 , low combustion temperature, short residence time, or an insufficient mixing of air and fuel in the combustion chamber. Incomplete combustion emits CO, polycyclic aromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), polychlorinated dibenzo-*p*-dioxins/dibenzofurans (PCDD/F), PM, and little amounts of ammonia (NH_3). In order to decrease the incomplete combustion emissions, excess air ratio above one (usually above 1.5) is needed in the combustion chamber to make sure of the inlet air mixing with fuel (Villeneuve, Palacois, Savoie, & Godbout, 2012). Table 14 shows the Egyptian ambient air quality standards including some critical pollutants that are often connected with biomass combustion such as $\text{PM}_{2.5}$, PM_{10} , CO, NO_2 , and SO_2 . For instance, Egypt has set an annual limit of $70 \mu\text{g}/\text{m}^3$ and a daily limit of $150 \mu\text{g}/\text{m}^3$ of PM_{10} (Egyptian Environmental Laws and Regulations, 2011). General air quality guidelines help in limiting adverse health effects caused by combustion of biomass. The World Health Organization (WHO) has recommended limits for such pollutants. Table 15 compares Egyptian, European, and North American ambient air quality with WHO

recommendations. Some pollutants' limits are the same for different standards like CO, which is $10 \mu\text{g}/\text{m}^3$ in the four standards, while others differ such as $\text{PM}_{2.5}$ that is 25, 80, 50, and 35 in WHO, Egypt, Europe, and USA standards, respectively. The authors stated that the replacement of fossil fuel with solid biomass needs other costs like ash removal procedures, fire insurance, meeting, air quality standards, general security, usage of proper biomass with the proper combustion technology, and finally air quality control equipment such as cyclones (Villeneuve, Palacois, Savoie, & Godbout, 2012).

Table 14 – Egyptian ambient air quality standards (Egyptian Environmental Laws and Regulations, 2011)

Pollutant	Maximum concentration (Egyptian Standards)	Averaging period
Fine particles ($\text{PM}_{2.5}$)	$80 \mu\text{g}/\text{m}^3$	24h
	$50 \mu\text{g}/\text{m}^3$	1 year
Sulphur dioxide (SO_2)	$350 \mu\text{g}/\text{m}^3$	1h
	$150 \mu\text{g}/\text{m}^3$	24h
	$60 \mu\text{g}/\text{m}^3$	1 year
Nitrogen dioxide (NO_2)	$300 \mu\text{g}/\text{m}^3$	1h
	$150 \mu\text{g}/\text{m}^3$	24h
	$60 \mu\text{g}/\text{m}^3$	1 year
PM_{10}	$150 \mu\text{g}/\text{m}^3$	24h
	$70 \mu\text{g}/\text{m}^3$	1 year
Lead (Pb)	$0.5 \mu\text{g}/\text{m}^3$	1 year
Carbon monoxide (CO)	$30 \text{mg}/\text{m}^3$	1h
	$10 \text{mg}/\text{m}^3$	Maximum daily 8 h

Ozone (O ₃)	180 µg/m ³	1h
	120 µg/m ³	Maximum daily 8 h

Table 15 - Egyptian, European, and North American ambient air quality standards compared with WHO recommendations (Villeneuve, Palacois, Savoie, & Godbout, 2012)

Pollutant	Maximum allowable level (µg/m ³)			
	WHO	Egypt	Europe	USA
Ozone (O ₃) (8h mean)	100	120	120	160
Fine particulate (PM _{2.5}) (24h mean)	25	80	50	35
Fine particulate (PM ₁₀) (24h mean)	50	150	50	150
Sulphur dioxide (SO ₂) (24h mean)	21	125	126	367
Nitrogen oxides (NO _x) (Annual mean)	39	60	39	100

Carbon monoxide (CO) (8h mean)	10	10	10	10
Lead (Pb) (24 h mean)	(-)	(-)	0.5	1.5

2.7 Combustion of RDF in Cement Kilns

Many researches have been conducted to evaluate the application of alternative fuels from waste in energy-intensive industries. Some of those studies are presented in this section to evaluate the use of RDF, which is a WTE source, in cement kilns that consumes enormous amounts of fuels.

A study conducted by Genon and Brizio (2008) discussed the use of RDF in cement kilns to obtain energy recovery. The use of RDF as a waste-to-energy solution was assessed from several aspects: the effects of RDF used in cement kilns on the emission of greenhouse gases, technological features and clinker characteristics, local atmospheric pollution, the economics of conventional solid fuels substitution and, finally, planning perspectives. Cement manufacturing plants are a suitable destination for RDF as a substitutive fuel material because of their capacity to sustain high temperatures making them an appropriate environment for thermal destruction of residuals without resulting in adverse environmental impacts. Cement plants have significant energy requirements of 3000-5000 kJ/kg of produced clinker. About 1.8 million t/y of secondary fuels were co-incinerated in more than 100 kilns across Europe in 1997 (Genon & Brizio, 2008). The related strategy for the cement industry is to depend on substitutive fuels for the sustainable development and to decrease the high energy bill incurred since energy costs represent approximately 30-40% of

manufacturing costs of Portland cement. According to Genon and Brizio (2008) RDF can be considered as a real technological solution for both the RDF producers and cement plant operators who seek optimal energy allocation, limiting environmental impacts and the economics of production. However, the authors acknowledge that there are some limitations such as the low calorific value and the chemical presence of atmospheric pollutants. Furthermore, the RDF substitution rate can be limited, and they suggest that some technological modifications as well as process parameter adjustments may be needed due to issues related to the kiln thermal and mass balances. Different conclusions have been drawn from the environmental point of view. Using RDF as an alternative fuel for coal or coke decrease greenhouse gas emissions, which complies with Kyoto parameters and emissions trading (Genon & Brizio, 2008). The conventional gaseous pollutants like Sulphur and chlorine are not critical since they are well retained by the alkaline micro-environment. Moreover, the presence of suspended fine dust, which is common in cement kilns, can be eliminated, and the generation of nitrogen oxides can be reduced due to lower flame temperatures or lower excess air. RDF may present some danger because of the heavy metals, especially the more volatile ones. RDF usually contains higher amounts of Sb, Hg, Cd, As, Pb, Cu, Cr, and Zn than those present in pet coke, but compared to coal, it also contains large amounts of Hg, Co, Cd, and Tl (Genon & Brizio, 2008).

Another study carried out by Kara et al (2009) investigated the process of producing RDF from non-recyclable wastes and the possibility of using it as an alternative fuel in the cement industry (Kara, Gunay, Tabak, & Yildiz, 2009). In this paper, the effects of using RDF on cement production were examined. In this study, RDF produced was mixed with liquefied petroleum gas (LPG) in different ratios (0, 5, 10, 15, and 20%). Afterwards, the produced cement clinker was analyzed chemically and mineralogically. The results obtained

from the chemical analysis of the cement produced using RDF as an alternative fuel showed that all values are within the allowable Portland cement values. It was also found that RDF is an economically feasible alternative for fossil fuels in cement production. Moreover, the study revealed that RDF produces a more homogeneous fuel that can be burnt more evenly at higher temperatures making the combustion process easier (Kara, Gunay, Tabak, & Yildiz, 2009).

A study conducted by Ozkan and Banar (2010) focused on the evaluation of RDF usage in the cement industry in terms of technical, economical, and social assessments. The authors used one of the Multi Criteria Decision Making (MCDM) tools called Analytic Network Process (ANP). Several scenarios were investigated and then the results were compared. The scenarios were: using coal as a fuel, using alternative fuels such as tires waste, oil waste, etc, the utilization of 10% RDF and 90% coal, using 40% RDF and 60% coal, and finally using 100% RDF as a fuel. Each of those scenarios was evaluated based on its advantages, costs, and risks. The criteria used in the benefits aspect was the use of fuel with high heating value that decreases the fuel quantity, saving fossil fuel, and environmental benefits. Moving to the cost, there are three types of costs, which are: the preprocessing costs to prepare fuel, fuel costs, and analysis costs for controlling emissions. Meanwhile, the following criteria were used to evaluate risks: standard emissions like SO₂, NO_x, and CO₂, and toxic gas emissions (Volatile Organic Compounds VOC, Polychlorinated dibenzodioxins and dibenzofurans PCDD/PCDF, Polychlorinated Biphenyls PCB). According to the abovementioned criteria, it was found that the 100% RDF scenario was the best scenario (Ozkan & Banar, 2010).

In 2010, Rovira et al. studied the influence of partial substitution of fossil fuel by RDF in a cement plant in Alcanar (Catalonia, Spain). Some surveys were performed for the

environmental monitoring before and after using RDF by a maximum replacement of 20% of the required energy, however, this percentage currently reached 30%. In order to carry out the investigation, samples from air, soil, and herbage around the facility were collected to analyze metals and PCDD/Fs levels. It was found that there was significant reduction in the levels of PCDD/PCDF and some metal concentrations. Also, the concentration of particulate matter (PM₁₀) was constant with a value of 16 µg/m³. For the population living nearby, both the carcinogenic and non-carcinogenic risks caused by the exposure to PCDD/PCDF and metals were found to be within the acceptable ranges according to national and international standards. Therefore, RDF can be considered as a successful alternative for fossil fuels (Rovira, Mari, Nadal, Schuhmacher, & Domingo, 2010).

In another study conducted by Askar, Jago, Mourad, and Huisingh (2010), the authors demonstrated that alternative fuels from waste has been used for more than 20 years in Europe and the USA. Several reasons have boosted the use of waste derived fuels (WDF) in cement kilns such as the high temperatures, long residence time, the alkaline environment in the cement kiln, and ash becomes part of the product which reduce left residues. The author stated that the government in Egypt has doubled the price of heavy fuel for energy-intensive sectors, and they also applied new tariffs for electricity in August 2010 on high electricity consumers like cement industry. This has led to increase in price that reached 50% on the peak energy consumption periods (7.30-11.00 pm in summer, and 5-9 pm in inter). This increase in prices has been the main driver to use alternative fuels in cement manufacturing such as RDF and agricultural wastes. However, other benefits can be obtained from using those alternative fuels, which make it a Cleaner Production option, such as reduction of waste disposed in landfills, energy recovery from combustible wastes, net reduction in emissions, conservation of fossil fuels, and reduction in cement production cost.

Cemex cement in Assiut was approximately substituting 15.2% of their fuel with agricultural wastes when this study was conducted, however, they were planning to increase this percentage. Also, Lafarge has already studied and started to apply the use of RDF. Table 16 shows some fuel substitution initiatives that took place in different cement facilities in Egypt when this study was carried out in 2010. For instance, the substitution percentage among those presented in this table was Cemex Cement in Assiut that substituted 21% of the used fuel with agricultural waste, while in Suez Cement in Helwan plant substituted conventional fuels with 15% agricultural waste, 10% RDF, and 5% other alternative fuels. Also, substitution of 10% RDF and 20% agricultural waste was used in Suez Cement, Katameya plant in Cairo. However, the rate of substitution in Egypt mainly depends on availability of alternative fuels and financial drivers, and it is anticipated to that the maximum substitution percentage would reach 30%, which has already implemented in some facilities by this time (2016) (Askar, Jago, Mourad, & Huisinigh, 2010).

Table 16 - Fuel substitution initiatives in Egypt (Askar, Jago, Mourad, & Huisingsh, 2010)

Initiatives of the companies	Fuel substitution	Agricultural waste	RDF	Other
		Tons x 10 ³ per year		
Suez Cement Helwan plant, Cairo (Italcementi group)	10-30%	166 15%	93 10%	54 5%
Suez Cement Katameya plant, Cairo (Italcementi group)	10-30%	89 20%	37 10%	
Amreya Cement, Alexandria (Cimpor)	Approximately 10%			
Lafarge Cement, Suez	Kiln 2		72	
	Kiln 1	120		
	Kiln 4			23
Cemex Cement, Assiut		15-21%	275 21%	

CHAPTER (3)

METHODOLOGY

3.1 Introduction

This research was divided into three phases. The first phase was conducted to get the calorific value of various solid waste materials from agricultural, municipal, and industrial sources. The selected materials of waste were chosen based on the literature. The agricultural wastes are categorized into two groups: agricultural crop residues (straw, stalks), and agro-industrial crop residues (leaves, kernels, shell, husk). The agricultural related wastes used here were: rice straw, rice husk, bagasse, corn husk, and onion leaves. From literature, corn cobs were examined earlier as an alternative fuel, however, corn husk was chosen in this study because it is a waste of no appreciable value to industries. The other wastes from municipal and industrial activities were: tires, various types of plastics, laminated plastics (chips and chocolate packaging bags) and wood residues from industrial activities (sawdust). Plastics included in this research were high-density polyethylene (HDPE), polypropylene (PP), polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polystyrene (PS). The second phase of the study was concerned with the effect of different binders and their percentage on the average calorific value of biomass pellets, while the third phase was carried out to trace emissions produced from the most promising waste materials to determine the proper mitigation technologies that should be used. The three phases of this research were conducted on lab scale.

3.2 Preparation of Waste Materials

In this research, various crop residues, plastics, and tires were selected to represent a portion of the agricultural, industrial, and municipal solid waste in Egypt. Agricultural wastes used in this study were firstly dried to reduce the moisture content before grinding. Since this study was conducted at a lab scale, the grain size of materials ranged between $63\mu\text{m}$ - 1.18mm. Materials were prepared as following:

- Rice straw was received in bales of tall straws, then it was dried under sunlight. A cutting machine (Figure 4) was used first to cut it into smaller straws. The output of the cutting machine is shown in Figure 5. Afterwards, the shorter rice straws were ground into finer particles using a chopping machine, shown in Figure 6.



Figure 4 - Feeding large rice straws into the cutting machine to be cut into smaller straws



Figure 5 - Rice straw output of the cutting machine



Figure 6 - Grinding rice straw into fine particles in a chopping machine

- Similar procedure was repeated for bagasse, corn husk, and onion leaves that got dried first under the sunlight, then ground with the same machine in Figure 6. The output material is illustrated in Figure 7.



Figure 7 – Ground onion leaves

- Wood (sawdust) was obtained as waste from furniture industry, so it was already received in small particles.
- Laminated plastics from chips and chocolate packaging were firstly washed, then left to dry under the sunlight. Afterwards, they were manually cut with scissors, and then they were cut into smaller particles with the crushing machine in Figure 8.



Figure 8 - Output of laminated plastics from the cutting machine

- In order to prepare PET, water bottles were cut into smaller pieces using cutter and scissors, then those small pieces were fed into the same machine in Figure 8 that has sieves with 1mm, 2mm, and 3mm diameter openings to obtain finer particles. The same procedure was carried out to cut foam plates into smaller particles to obtain polystyrene using the sieve with 2 mm diameter openings for both PET and PS.
- HDPE, PVC, and PP were received as they were, thus no further preparation was needed.
- Tires were also cut into small pieces manually with scissors, then crushed into finer particles with the cheese machine shown in Figure 9.



Figure 9 - Cutting tires into finer grains using cheese machine

- Sieve analysis test was performed to determine the grain size of the used waste materials within the given samples. It was anticipated that grain size does not influence the material's calorific value. However, rice straw, corn husk, and tires were grouped into two size ranges to make sure that grain size does not affect the average calorific value of waste material. Table 17 shows the grain size of each material:

Table 17 - Grain size of the investigated waste materials

Material	Grain size
Rice straw	63µm - 425µm, 850µm - 1.18mm
Rice husk	106 µm – 1.7mm
Corn husk	63µm - 425µm, 850µm - 1.18mm
Bagasse	63µm - 425µm
Onion leaves	< 710µm
Sawdust	<1.18mm
Tires	63µm - 425µm, 850µm - 1.18mm
Laminated plastics	106µm – 1.7mm
PET	<2.00mm
PP	425µm – 2.00mm
HDPE	106µm – 850µm
PVC	106 µm – 2.00mm
PS	106µm – 1.18mm

- In order to get the moisture content of biomass materials, a sample of each of the six tested biomass materials: rice straw, rice husk, corn husk, onion leaves, bagasse, and sawdust was weighed and then dried in an oven at 105 °C until the sample achieved a constant weight (ASTM, 2010). Afterwards, the sample was cooled in a desiccator and then weighed again. The moisture content was calculated on a wet basis by Equation 1:

$$\text{Moisture content (\%)} = \frac{\text{wet mass (g)} - \text{dry mass (g)}}{\text{wet mass (g)}} \times 100 \quad (1)$$

3.3 Phase I – Investigation of the Average Calorific Value

In order to measure the average calorific value of the selected waste materials, an oxygen bomb calorimeter (XRY-1A) (Figure 10) was used. The used bomb calorimeter was made and designed as per the National Standard of People's Republic of China GB/T213-2008. A sample of 0.53 g of each material was tested five times and then the average calorific value was calculated. The calorific value of sample is the heat produced when burning a unit mass in the oxygen bomb that contains excessive oxygen (J/g or kJ/kg).



Figure 10 - XRY – 1A Oxygen bomb calorimeter

3.3.1 Materials

1. Benzoic acid of grade two or higher standard heat measurement substance was used to calibrate the equipment.
2. Ignition wire made of nickel chrome wire with a diameter of 0.1 mm.
3. Oxygen that should be industrial oxygen with purity of 99.5%, and it should not contain hydrogen or any other combustible substance.

3.3.2 Methods

The following procedure was carried out to measure the calorific value of waste materials by the oxygen bomb calorimeter:

1. The outer bucket in the bomb calorimeter was filled with water and stirred until the water's temperature is even.
2. The inner bucket was also filled with about 3000 g of water and the water's temperature in the inner bucket should be 0.2~0.5 °C less than the outer bucket.
3. The first measured sample was standard benzoic acid to calibrate the equipment. The benzoic acid's sample was weighed and placed in the crucible.
4. The crucible was then fixed to the crucible holder and ignition wire was fixed on the two conductive poles of the oxygen bomb. The ignition wire should just touch the sample surface, and a 10 ml of distilled water was added into the oxygen bomb.
5. The cover of the oxygen bomb was tightly screwed, and then oxygen was filled until the pressure in the oxygen bomb was 2.8~3.0 MPa.
6. The oxygen bomb was then placed on the oxygen bomb seat in the inner bucket that was filled of water. The water's surface in the inner bucket should be at about 2/3 of the screw cap of oxygen inlet valve of the oxygen bomb.
7. The ignition connection wire and all other wires were connected on the controlling case. The instrument cover was closed, and the temperature sensor was inserted into the inner bucket.
8. The instrument was turned on, the Stir button was pressed, and temperature of the inner bucket was shown every half minute. After the temperature reached a constant value, Ignite button was pressed at the same time, and the measurement time got

zeroed automatically. Again, the instrument recorded temperature data every half minute until it got 31 readings, and the End button was pressed to end the test.

9. Finally, stirring was stopped, the sensor was taken out, the instrument cover was opened, and the oxygen bomb was taken out. The oxygen in the oxygen bomb was discharged using a discharge valve to check if the sample has completely burned, then the test data is valid.
10. From the obtained data, calorific value of the sample was calculated using the following equations (Equation 2, 3):

$$E = \frac{Q_1 M_1 + 40}{\Delta T} \quad (2)$$

Where,

E = Heat capacity (J/°C)

Q₁ = Heat value of standard benzoic acid (26456 J/g)

M₁ = Mass of benzoic acid (g)

ΔT = Temperature increase (T_f – T_i) in the calorimeter system (°C)

$$Q = \frac{E \cdot \Delta T - 40}{G} \quad (3)$$

Where,

Q = Heat value of sample (J/g)

E = Heat capacity of the instrument (J/°C)

ΔT = Temperature increase (T_f – T_i) in the calorimeter system (°C)

G = mass of sample (g)

11. The average calorific value of five samples of each material was calculated, and the above steps were repeated to measure other samples.

3.4 Phase II – Pellets

In the second phase of this study, the impact of different binders on the calorific value of biomass pellets was investigated. Based on international standards, the moisture content of pellets should be $< 10\%$, and binders' percentage should be $\leq 2\%$. The moisture content of biomass materials used in this study ranged between 7.0 – 7.3 wt% (wet basis). Mass of 0.53 g for each biomass sample (rice straw, rice husk, corn husk, bagasse, onion leaves, sawdust) was pelletized using the compressing machine, shown in Figure 11, and all samples were pelletized under the same compression force. Each binder was added in 0, 2, and 4%, and five samples of each material was tested. The same steps stated in the previous section (phase I) were repeated to measure the calorific value.



Figure 11 - Compressing machine for pellets

3.5 Phase III – Emissions from Different Waste Materials

In the third phase of this study, the most promising materials determined from phase I were combusted to inspect the approximate emissions produced from those materials relative to each other. For industries that can use those alternative fuels, this would facilitate the process of determining what mitigation and air control technologies should be used to minimize air pollutants and comply with standards. Emissions were detected with a Testo-350 gas flue analyzer (Figure 12). The Testo-350 gas analyzer measured CO, NO, NO₂, and SO₂ in ppm, while CO₂ was given in percentage. The following steps were taken to measure emissions:

1. A muffle furnace was heated to 850 °C (Figure 13).
2. The gas analyzer was turned on, while the probe was placed in fresh air. The instrument takes about 60 seconds carrying out a self-test and rinsing the measuring cells with fresh air. It also detects the temperature of fresh air at that time. Once the self-test ended, O₂ percentage was shown as 21.0%, and if not, it must be set at 21.0%.
3. A Parameters button was pressed and then jumped to the measurement menu. At this stage, the instrument was ready to start measuring.
4. The flue gas probe was placed in the center of the flow through an opening in the furnace's ceil. Then, the pump was started and readings were taken every one minute until the combustion process ended, and this was observed from the instrument's readings that got very low or zeroed. The remained mass after combustion was weighed.

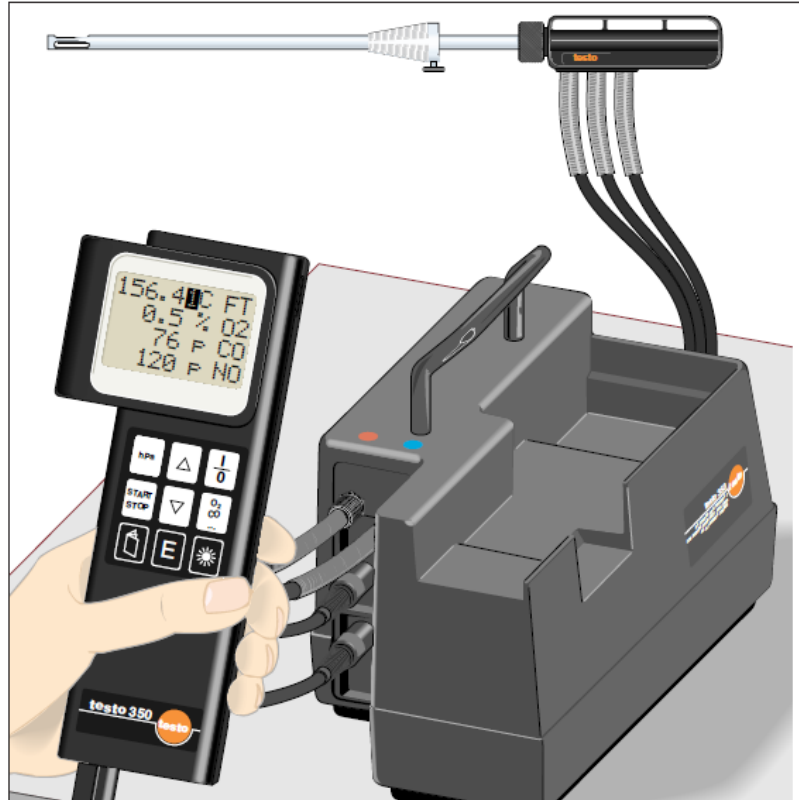


Figure 12 - Testo-350 flue gas analyzer

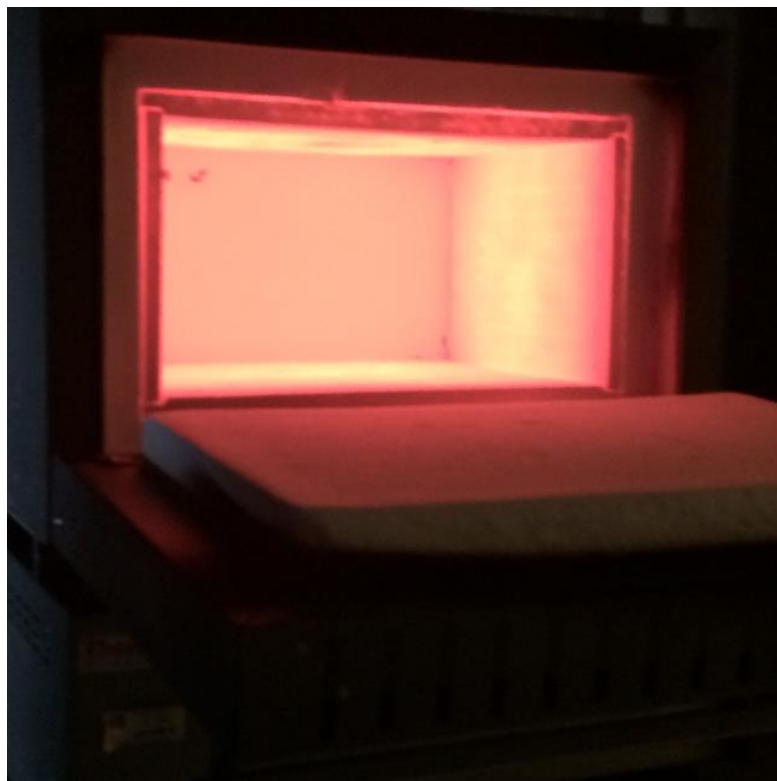


Figure 13 - An insulated oven heated at 850 °C

CHAPTER (4)

RESULTS AND DISCUSSION

4.1 Phase I - Calorific Values

The calorific values of different waste materials (municipal, industrial, and agricultural) were investigated to determine which materials are the most promising to be used as a source of energy. The calorific value (CV) of each material was measured five times to ensure accuracy, and then the average of the five values was taken.

4.1.1 Average calorific values of agricultural waste

The results show that the highest average calorific values of the selected agricultural waste were obtained from bagasse, then corn husk, which were 17309 kJ/kg, and 16911 kJ/kg with standard deviation of 2.96%, and 2.38 %, respectively. Comparing both rice straw and rice husk, there was no large difference between the two, however, rice husk gave greater average calorific value of 15178 kJ/kg and standard deviation of 2.47%, while rice straw's average calorific value was 14435 kJ/kg with standard deviation of 1.59%. Onion leaves' average calorific value was very close to that of rice straw, which was 14340 kJ/kg with a standard deviation of 3.32 %. Figure 14 shows the selected five agricultural wastes and their average calorific values.

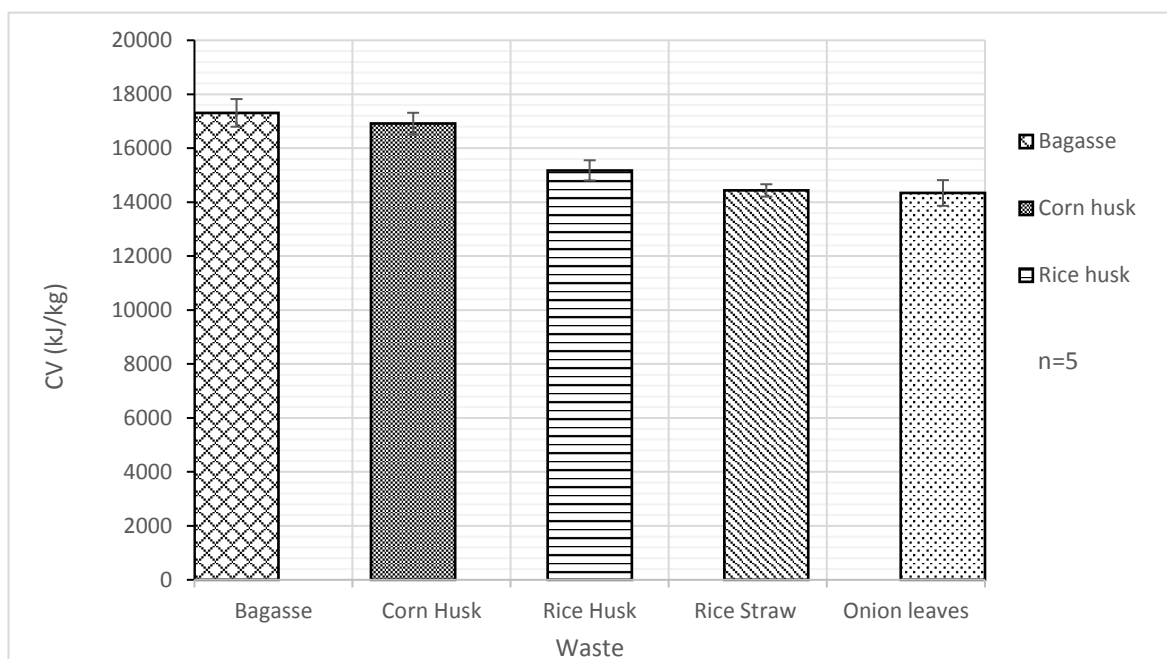


Figure 14 - The average calorific values of the selected agricultural wastes

4.1.2 Average calorific values of industrial and municipal solid waste

As presented in Figure 15 **Error! Reference source not found.**, PP achieved the highest average calorific value among all the measured plastics with an average calorific value of 47390 kJ/kg, while PVC gives the least value of 15245 kJ/kg, with standard deviation of 0.33%, and 2.09%, respectively. The average calorific value of HDPE is relatively close to PP with average calorific values of 46609 and 47390 and kJ/kg, respectively. The standard deviation of HDPE's average calorific value was 0.68%. Another material is laminated plastics that is used widely to manufacture chips and chocolate packaging, and it has an average calorific value of 38373 kJ/kg with standard deviation of 2.91%, which is even greater than PET and PVC's calorific values of 23483 and 15245 kJ/kg, and standard deviation of 2.87 and 2.09%, respectively. The average calorific value of tires was 31731 kJ/kg with standard deviation of 0.87%, while the sawdust produced by different industries gives average calorific value of 18177 kJ/kg with 2.06% standard deviation. From the results obtained in this phase, it could be highlighted that laminated

plastics can be considered as a potential source of energy that could not be found in the literature. It has a relatively high calorific value that is even higher than the calorific value of tires and other types of plastics like PET and PVC.

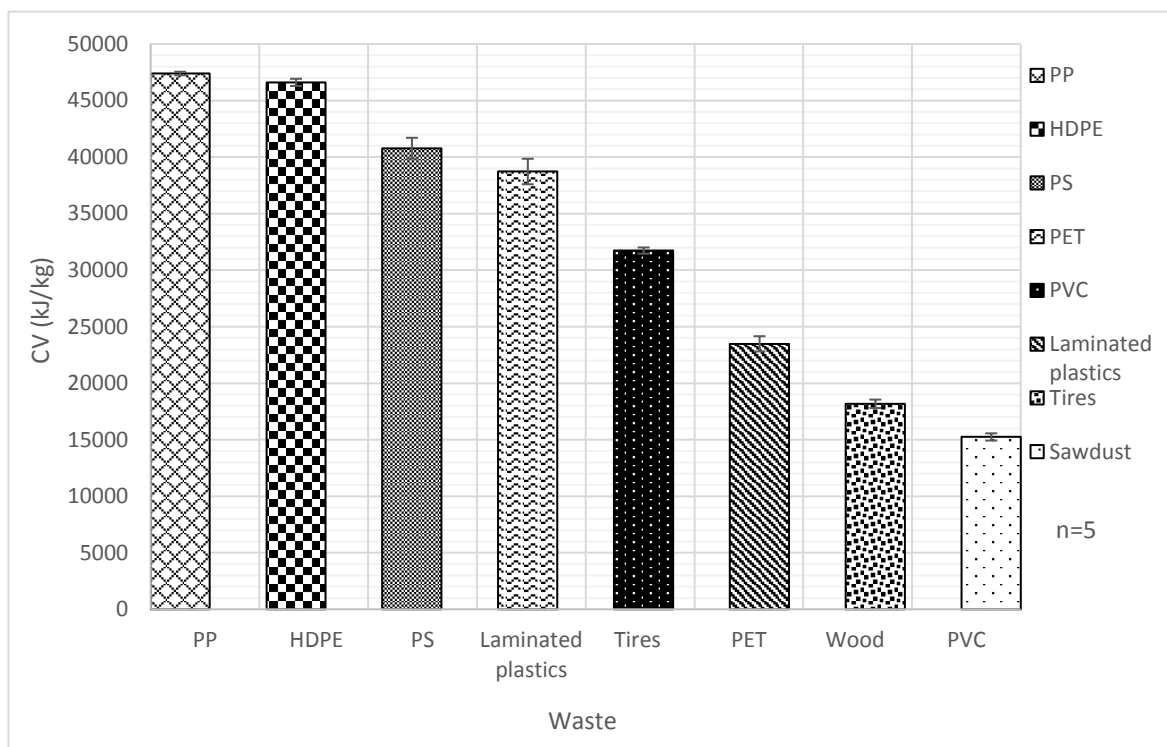


Figure 15 - The average calorific values of the selected industrial and municipal solid waste materials

4.1.3 Validation of the average calorific values

The average calorific values obtained using the bomb calorimeter in this study were validated by comparing them with values from literature. As shown in Table 18, the comparison demonstrates that both values were very close, with minor differences. The maximum difference reached about 19.8 % for PVC, while for the rest of the materials it ranged between 0.5-11.9 %. Those errors could be resulted due to many factors such as the source of materials that might accordingly change its physical properties like moisture content of the waste.

Table 18 - Comparison between average calorific values obtained from bomb calorimeter and the literature

Material	CV (kJ/kg) – Bomb calorimeter	CV (kJ/kg) – Literature	Error %	Reference
PP	47390	44000	7.7	(Themelis, Castaldi, Bhatti, & Arsova, 2011)
HDPE	46609	44000	5.9	
PS	40784	41000	0.5	
PET	23483	24000	2.2	
PVC	15245	19000	19.8	
Tires	31731	29000-36000	9.4 - 11.9	(Singh, Nimmo, Gibbs, & Williams, 2009)
Sawdust	18177	20000	9.1	(Capareda, 2011)
Rice Straw	14435	15200	5.0	(Capareda, 2011)
Rice Husk	15178	15400	1.4	

4.1.4 Effect of Grain size on the calorific value

Two grain sizes of three materials: rice straw, corn husk, and tires were tested in order to be used as indicator to ensure that grain size does not have impact on the calorific value of materials. The results in Figure 16 shows that the grain size was unlikely to affect the calorific value of materials. As for rice straw and tires, the difference between both values was less than 1%, while for corn husk it was 1.2%. However, it is speculated that the grain

size will more likely to have impact on the combustion behavior, which could not be examined in this study due to some limitations.

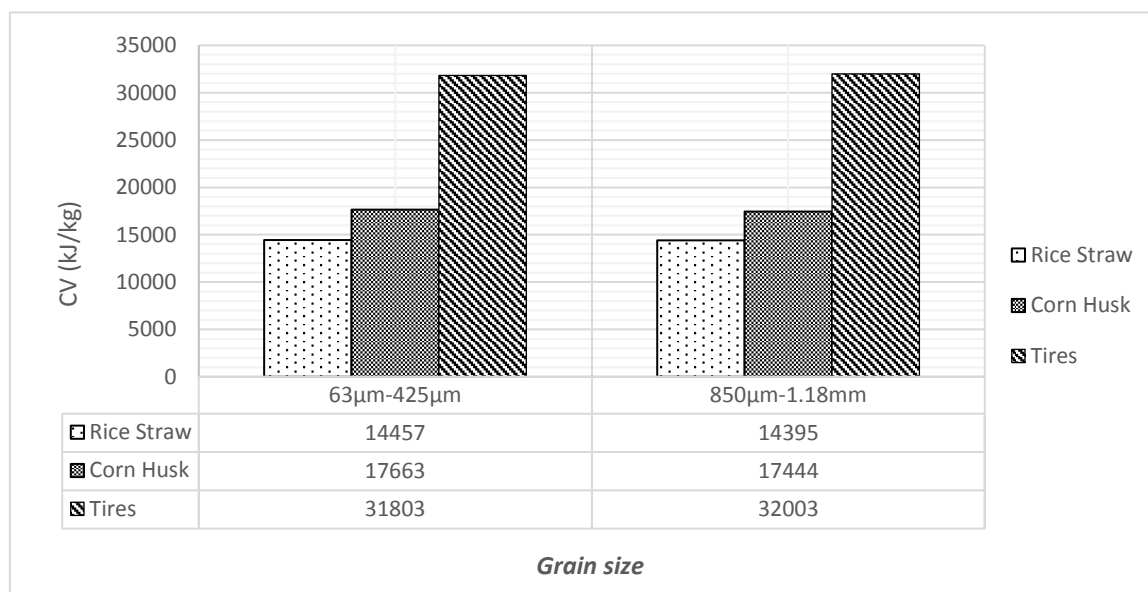


Figure 16 - Effect of Grain size on the calorific value

4.2 Phase II - Pellets

As mentioned in Chapter 2, pellets can make transportation, storage, and handling easier to manage biomass. Pellets should satisfy certain standards based on the following characteristics: bulk density, mechanical durability, dimensions, ash content, calorific value, moisture content, binding agent/additives percentage and others. However, the focus of this research is to investigate the average calorific value of pellets with different percentages and types of binders. The used binders were water, starch, and calcium hydroxide $\text{Ca}(\text{OH})_2$, which were selected based on literature. Each binder was tested at 0, 2, and 4 wt% of biomass.

The results obtained using starch, $\text{Ca}(\text{OH})_2$, and water as binders (Table 19) does not significantly affect the average calorific value of the tested biomass: bagasse, rice straw, rice husk, corn husk, onion leaves, and sawdust. For example, Figure 17 illustrates

that starch had a minor effect, when used as a binder, on the average calorific value of bagasse, rice straw, corn husk, rice husk, onion leaves, and wood, and similarly for Ca(OH)_2 , and water.

For rice straw, corn husk, and wood (sawdust), it was found that as the percentage of water increased, the average calorific value decreased. However, the reduction was minor within range of 3.3 – 6.3% of the pellet's average calorific value with 0% binder. The minimum decrease of 3.3% took place at 2% water for corn husk, while the maximum decrease of 6.3% occurred at 4% water rice straw. The other biomasses: bagasse, rice husk, and onion leaves did not show an exact trend, however, the changes were also minor and ranged between 0.3 – 6.0%.

For starch, the results obtained acted in a similar trend to bagasse, rice husk, and onion leaves with water as a binder. The differences happened in the average calorific value of the six biomasses were in range of 0.6 – 5.4%, with the maximum at wood with 4% starch, and the minimum at corn husk with 2% starch.

For Ca(OH)_2 , the average calorific value of rice straw, corn husk and wood pellets decreased with increasing the percentage of Ca(OH)_2 , same as in water. However, the changes ranged between 1.2 – 13.3%, with the minimum change of 1.2% occurred at rice straw with 2% Ca(OH)_2 , while the maximum was at wood with 4% Ca(OH)_2 . The results of remaining wastes: bagasse, rice husk, and onion leaves were also similar to pellets of the same materials with water as a binder. Change in the average calorific value of those materials ranged between 0.6% - 9.6%. The highest change took place in onion leaves pellets with 2% Ca(OH)_2 binder, while the lowest difference in calorific value was at 4% Ca(OH)_2 bagasse.

The obtained results might have been influenced with some factors that could have resulted in minor errors accordingly. Although it was ensured that the binder had been mixed very well with the biomass sample, there might have been some discrepancies in the sample's homogeneity. Also, the room temperature could also affect the sample's temperature, which could consequently cause those minor changes. However, the results showed that the three binders: starch, water, and $\text{Ca}(\text{OH})_2$ did not affect the average calorific value of biomass dramatically, but more research is still needed in this area to examine other properties such as density, mechanical durability, ash content, emissions and others in order to be able to determine the optimum binder to be used.

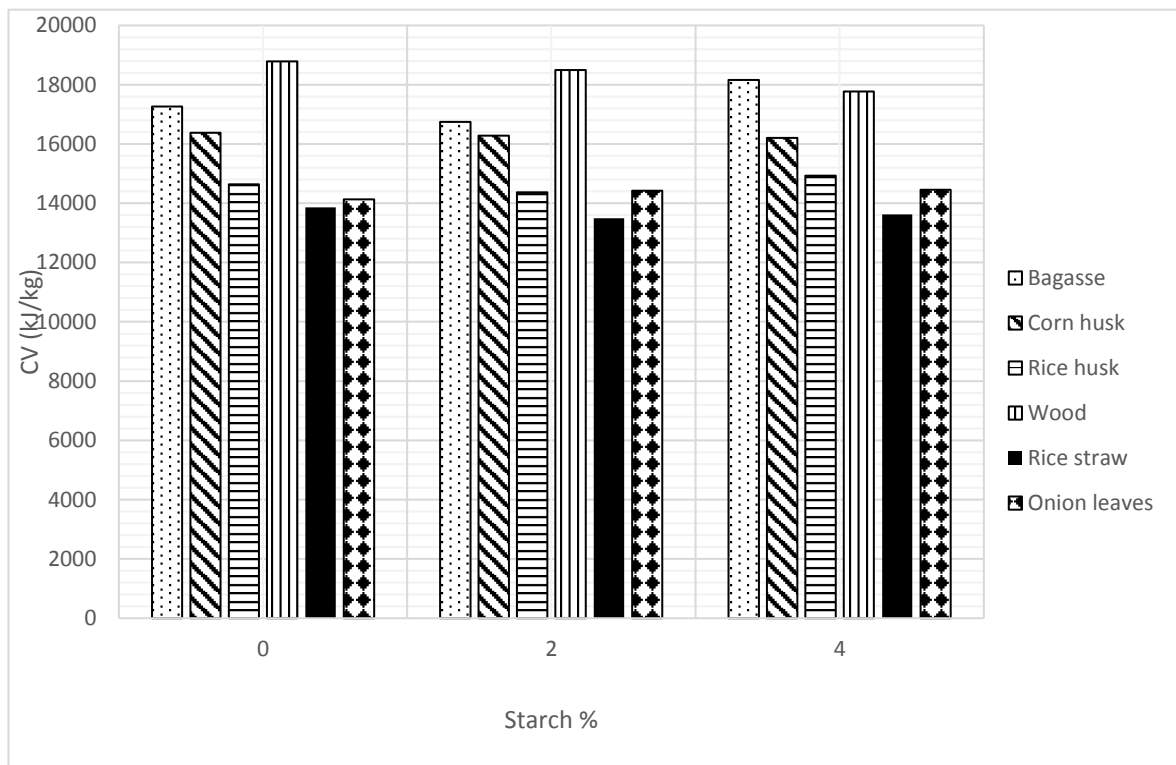


Figure 17 - Effect of starch as a binder on average calorific value of the selected biomass materials

Table 19 – Calorific values of biomass pellets

Material		Loose Calorific Value (kJ/kg)	Pellets						
			% Binder	Starch		Ca(OH)2		Water	
				Calorific value (kJ/kg)	Standard Deviation %	Calorific value (kJ/kg)	Standard Deviation %	Calorific value (kJ/kg)	Standard Deviation %
Bagasse	17309	0	17263	5.98	17263	5.98	17263	5.98	
		2	16750	0.84	17435	3.82	18291	0.88	
		4	18163	0.11	17363	1.05	17163	3.41	
Rice Straw	14435	0	13864	6.26	13864	6.26	13864	6.26	
		2	13493	0.9	13702	2.47	13217	1.75	
		4	13621	2.22	13421	3.46	12993	7.00	
Rice Husk	15178	0	14635	5.48	14635	5.48	14635	5.48	
		2	14364	0.54	14235	2.02	14474	2.86	
		4	14935	3.38	14893	2.35	14693	2.75	
Corn Husk	16378	0	16378	7.46	16378	7.46	16378	7.46	
		2	16278	0.62	15421	7.98	15835	3.06	
		4	16206	0.25	15350	3.95	15792	4.22	
Onion Leaves	14340	0	14136	0.71	14136	0.71	14136	0.71	
		2	14421	4.06	12779	1.69	14588	9.45	
		4	14450	0.42	13093	0.62	14226	10.00	
Wood	18177	0	18782	0.89	18782	0.89	18782	0.89	
		2	18492	2.95	18320	8.6	18106	3.68	
		4	17775	0.68	16278	8.07	17980	0.2	

4.3 Phase III –Emissions from Different Waste Materials

4.3.1 Selection of the most promising waste materials

From both literature and the abovementioned results obtained from phase I, it was found that bagasse is the most promising material among the tested agricultural wastes in terms of the average calorific value, which is 17309 kJ/kg for bagasse. Furthermore, rice straw can also be used as a potential WTE source instead of open-field burning that causes serious environmental problems due to its availability in large quantities and its average calorific value of 14435 kJ/kg. On the other hand, polypropylene and tires were selected as the most promising WTE materials from the tested municipal and industrial wastes. Polypropylene was found to have the highest average calorific value among the five investigated plastics with an average calorific value of 47390 kJ/kg, while tires can also be considered as a promising source of energy because of its abundance in enormous amounts in addition to the relatively high average calorific value of 31731 kJ/kg. All selected materials have a satisfying calorific value when compared with some other common fossil fuels like coal, which have a heating value within range of 15003 – 25772 kJ/kg. Also, diesel, which is commonly used as a source of energy, has a calorific value of 44799 kJ/kg that is close to the calorific value of polypropylene as well as other types of plastics (Sadaka & Johnson, 2014).

4.3.2 Emissions from different waste materials

As mentioned in Chapter 3, the obtained concentrations from Testo gas analyzer for CO, NO, NO₂, and SO₂ were in ppm, while CO₂ was given in vol%. The following figures (Figure 18, Figure 19, Figure 20, Figure 21, and Figure 22) show concentrations obtained from the gas analyzer for each type of emission over time:

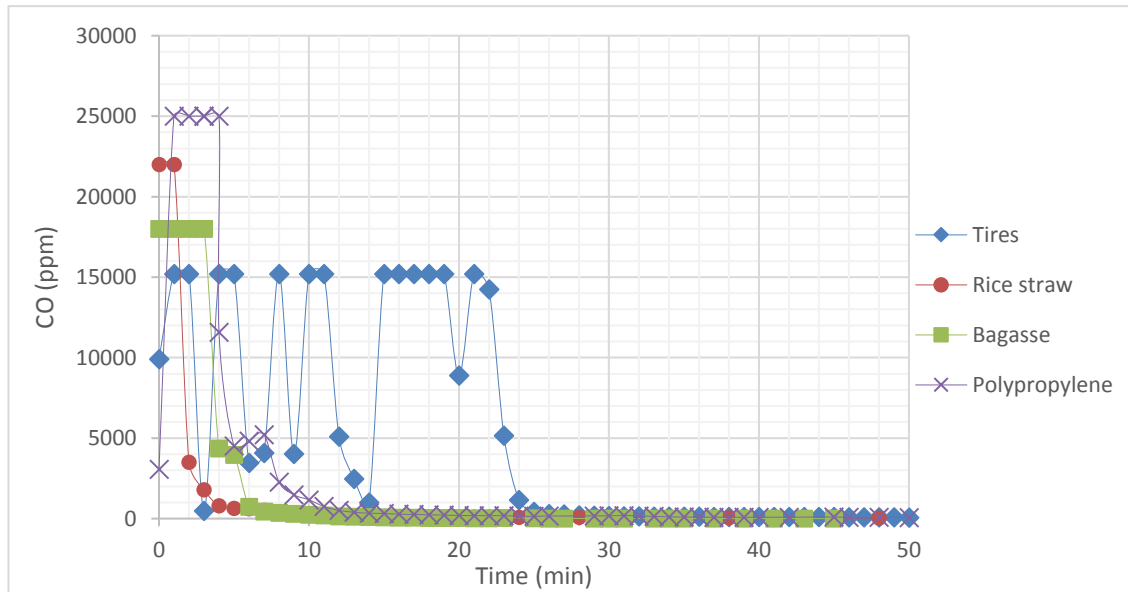


Figure 18 - Concentration of CO in ppm with time for the four tested materials

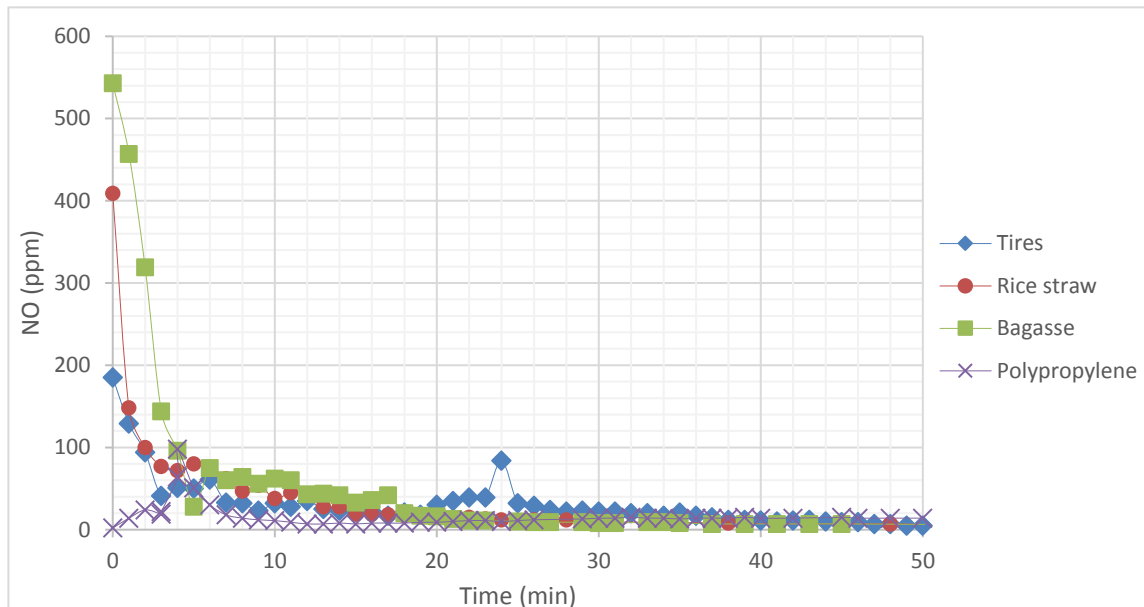


Figure 19 - Concentration of NO in ppm with time for the four tested materials

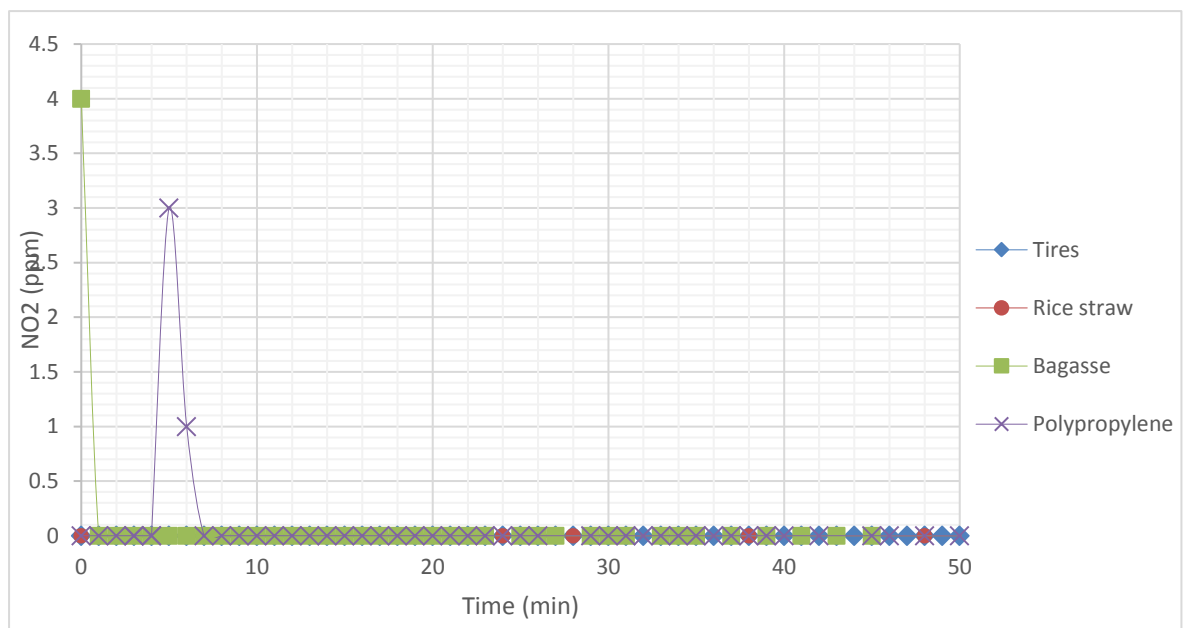


Figure 20 - Concentration of NO₂ in ppm with time for the four tested materials

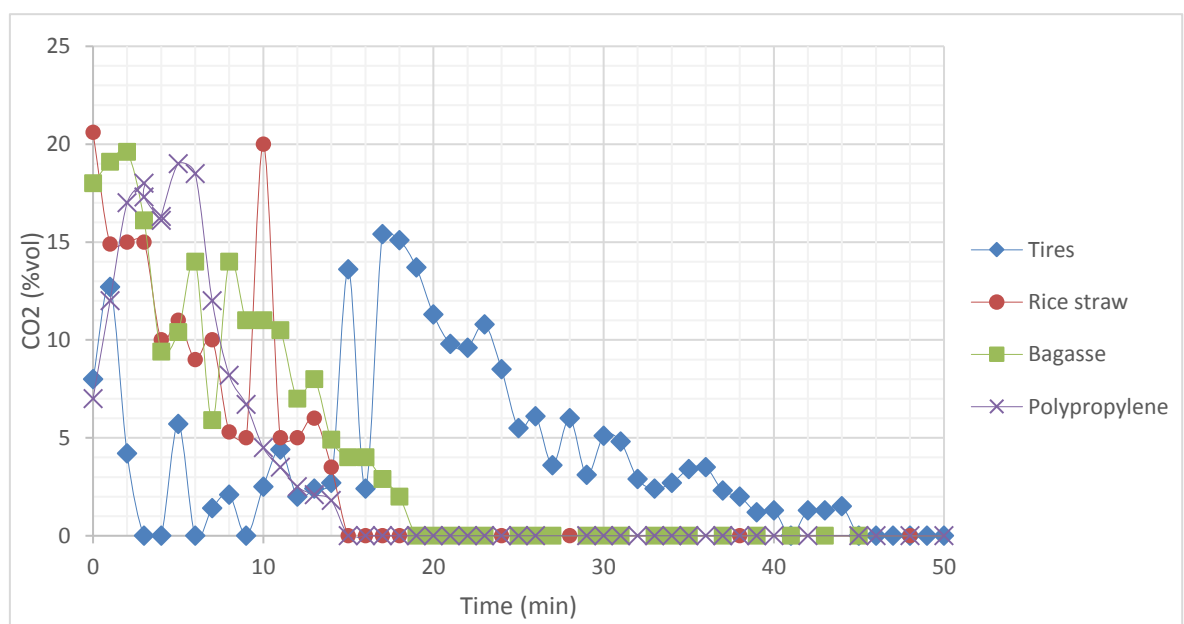


Figure 21 - Concentration of CO₂ in (%vol) with time for the four tested materials

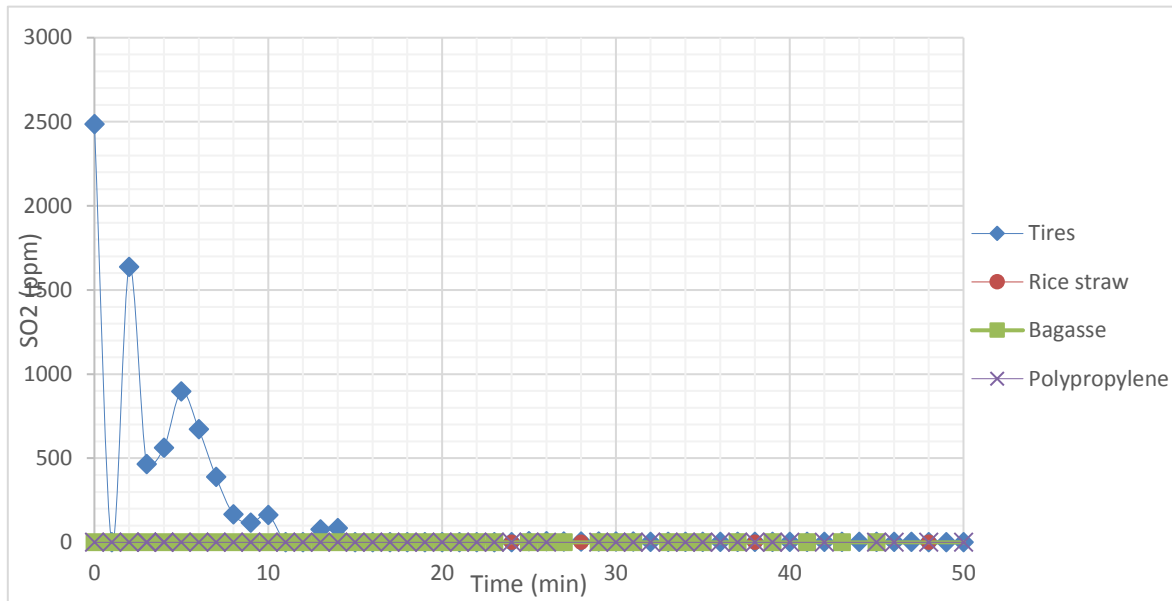


Figure 22 - Concentration of SO₂ in ppm with time for the four tested materials

Results were normalized to express the amount of each pollutant as mass per unit mass of the burned material to be compared to each other. In order to be able to get the mass of each pollutant, concentrations were firstly converted from ppm into mg/m³. The percentage of CO₂ was converted into ppm, as 1% is equivalent to 10,000 ppm. The following equation (Equation 4) was used to convert from ppm to mg/m³:

$$\text{mg/m}^3 = \frac{\text{ppm} \times M}{0.08205 \times T} \quad (4)$$

where,

M: molecular weight of gas

T: temperature of combustion in Kelvin (°C+273)

0.08205: universal gas constant

Then, the resulted concentration in mg/m³ was multiplied by the furnace volume, which was 0.0188 m³. Afterwards, the area under each curve was calculated by taking stripes with width of one minute and height of the average value of the concentrations of each pollutant, and then all areas were summed to get the total mass of each pollutant. The resulted

mass was then divided by the total burned mass of each material. All pollutants of each material were added up together to get the total output mass in grams (g), and the remained mass was weighed to get percent of losses.

The area under the curve, which is presented as mass of CO per unit mass of rice straw, bagasse, tires, and polypropylene in a minute were 12.56, 19.15, 56.56, and 38.16 g.min/kg, respectively, as shown in 23, which means that tires had the highest value of CO emission, then polypropylene. Also, bagasse emitted CO more than rice straw.

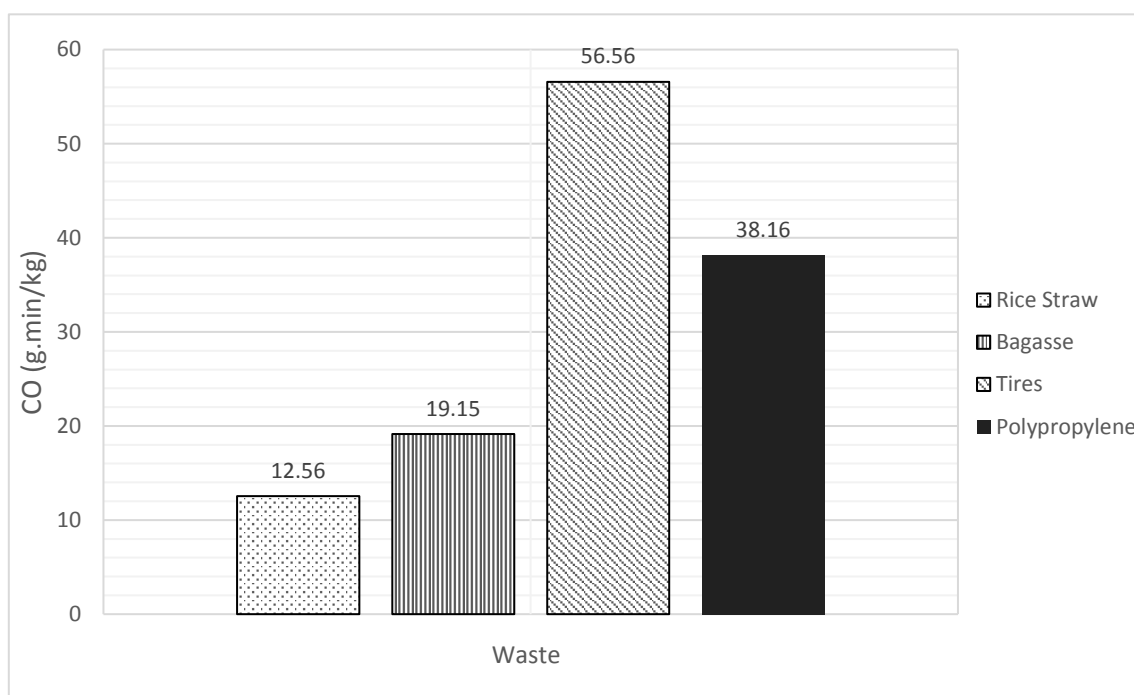


Figure 23 - CO pollutant emission factors from burning rice straw, bagasse, tires, and polypropylene

The mass of NO per unit mass of rice straw, bagasse, tires and polypropylene were 0.39, 0.59, 0.35, and 0.18 g.min/kg, respectively (Figure 24), meaning that polypropylene had the lowest value of NO, while bagasse produced the highest value, then rice straw.

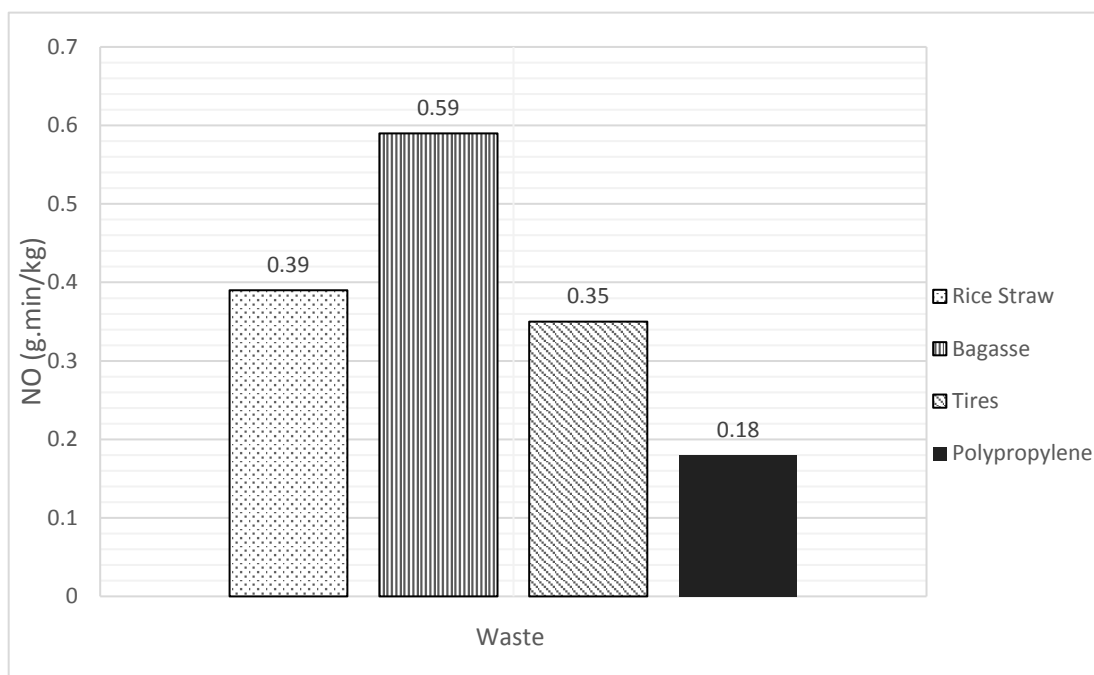


Figure 24 - NO pollutant emission factors from burning rice straw, bagasse, tires, and polypropylene

As illustrated in Figure 25, the mass of NO₂ per unit mass of rice straw, bagasse, tires, and polypropylene was 0, 0.012, 0.012, and 0.0016 g.min/kg, respectively. The amount of NO₂ produced from bagasse and tires were almost the same and they gave the maximum value, while rice straw did not emit NO₂ at all.

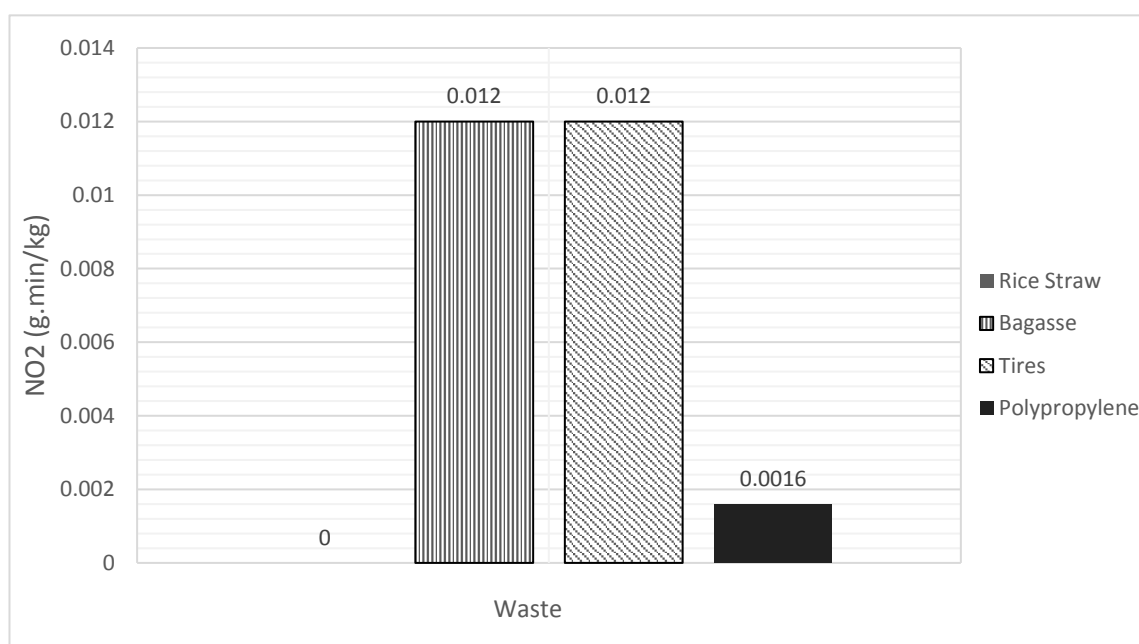


Figure 25 – NO₂ pollutant emission factors from burning rice straw, bagasse, tires, and polypropylene

The mass of SO₂ per unit mass of rice straw, bagasse, tires and polypropylene were 0, 0, 2.73, and 0g.min/kg, respectively as demonstrated in Figure 26. From these values, it was observed that tires were the only material that produced SO₂ emissions.



Figure 26 - SO₂ pollutant emission factors from burning rice straw, bagasse, tires, and polypropylene

The mass per unit mass of CO₂ for rice straw, bagasse, tires and polypropylene was 552.56, 685.68, 745.6, and 662.64 g.min/kg, respectively as shown in Figure 27. The maximum value of CO₂ was produced from tires, then bagasse. The minimum value was obtained from rice straw.

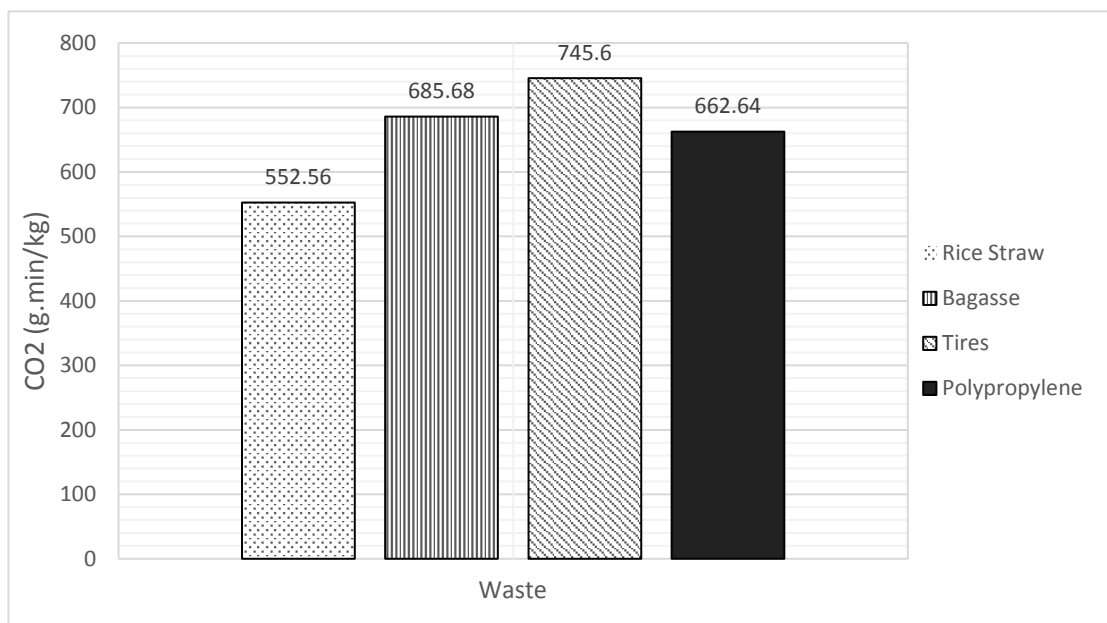


Figure 27 - CO₂ pollutant emission factors from burning rice straw, bagasse, tires, and polypropylene

Mass loss in tires mass, which is the total burned mass minus remaining mass and mass of produced emissions, was the minimum with value of 3% loss, while the maximum mass loss was 28% in polypropylene. For rice straw and bagasse, the mass loss was 16%, and 25%, respectively. Those mass losses may have affected the obtained results. According to Irfan et al. (2014), it was reported that rice straw reached a mass loss of 19% in a previous study, although other materials normally have mass losses of 10%. The authors also stated that variations in combustion conditions and fuel properties could result in high degree of uncertainty and rough estimates (Irfan, et al., 2014).

Many different factors could have impacted the combustion process, which may have resulted in discrepancies in values of emissions, such as the mass loss, and the inability to measure all emissions with the Testo gas analyzer. Also, those values can differ from one test to another even for the same material due to differences in the combustion conditions, and in chemical composition of C, S, and N of the burned material, in addition to the moisture content (Irfan, et al., 2014). Another issue that should be taken into consideration is that the Testo gas analyzer gives rough estimation for emissions that enabled conducting a comparative study between different wastes, and not accurate values.

CHAPTER (5)

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Alternative fuels can be a clean source of energy and an optimum solution for energy crisis and depletion of fossil fuels. Furthermore, waste-to-energy can contribute in solving the waste management problem in Egypt. The main objective of this research was to provide the energy-intensive industries with a database of the calorific value of various solid waste materials and the anticipated pollutant emissions of the most promising ones. Also, it compared between the effect of different binders that can be used to enhance the palletization process of biomass. The main findings of this study are summarized in the following points:

- From the first phase, it was found that all used wastes have a reasonable calorific value when compared to coal's calorific value, which is 15003-25772 kJ/kg. The minimum calorific value of 14340 kJ/kg \pm 3.32% was provided by rice straw, and the maximum calorific value among agricultural wastes was bagasse with a calorific value of 17309 kJ/kg \pm 2.96%. The highest calorific value among all measured wastes was given by polypropylene with a value of 47390 kJ/kg \pm 0.33%, while tires had a calorific value of 31731 kJ/kg \pm 0.87%,. However, the most promising waste materials were selected based on their calorific value and abundance. Therefore, bagasse, rice straw, polypropylene, and tires were chosen to investigate their emissions in phase three.

- Laminated plastics, which have not been investigated earlier in the literature, could be a potential waste-to-energy material that has a relatively high calorific value of $38273 \text{ kJ/kg} \pm 2.91\%$.
- In the second phase of this study, it was demonstrated that the three binders: starch, water, and Ca(OH)_2 , did not have a significant effect on the calorific value of the tested biomasses: rice straw, rice husk, corn husk, bagasse, onion leaves, and wood (sawdust), when added in 0, 2, and 4%. However, the maximum change of 13.3% of the average calorific value took place in wood with 4% Ca(OH)_2 , while the lowest change occurred in bagasse with 4% Ca(OH)_2 .
- The third phase of the study compared between the released emissions of CO, NO, NO_2 , SO_2 , and CO_2 from rice straw, bagasse, tires, and polypropylene in terms of mass of pollutant per unit mass of the burned material. The mass of CO and CO_2 per unit mass of tires were 56.56 g.min/kg , and 745.6 g.min/kg , respectively, which was the maximum among the four combusted materials. The lowest values of CO, and CO_2 were 12.56 g.min/kg , and 552.56 g.min/kg , respectively, and were produced by rice straw. Bagasse had the highest mass of NO per unit mass of bagasse, which was 0.59 g.min/kg , and polypropylene was the minimum with a value of 0.18 g.min/kg . The mass of NO_2 per unit mass of bagasse and tires were almost the same with a value of 0.012 g.min/kg . SO_2 mass per unit mass of tires was 2.73 g.min/kg , which is the highest value among the four selected materials, while rice straw, bagasse, and polypropylene did not produce SO_2 . However, those values could have been impacted by some factors such as mass loss, which reached its maximum in polypropylene with a value of 28%, and those pollutants that could not be measured by the Testo gas analyzer. Also, the combustion conditions, moisture content, and chemical composition of C, S, and N of

the burned material should be considered as they are likely to have impact on the produced emissions if the test is repeated.

5.2 Recommendations

In order to maximize the benefits of this study, further extensive research should be conducted to enhance its findings. The following points are recommended to be examined in the future:

- Further research should be done to investigate the use of laminated plastics as an alternative fuel that includes emissions produced from laminated plastics combustion, and estimation of the amounts of laminated plastics in Egypt.
- Investigation of the effect of starch, water, and Ca(OH)_2 on other properties of pellets such as particle density, bulk density, dimensions, and fuel stability.
- Studying the effect of temperature and compressive force on density and durability of pellets.
- Studying the effect of grain size on the combustion behavior.
- More research is required in the area of combustion to decide on the proper combustion technology and proper temperature that should be used to burn each waste material.
- A field study should be conducted to evaluate emissions in the field, since those measured in the laboratory may differ from those obtained in the field.
- Estimate the total amount of waste produced from each material and estimate the total gaseous pollutant emissions of CO, CO₂, NO, NO₂, and SO₂ from each material in a year, in order to be able to compare them with standards, and choose mitigation measures and air control technologies that should be applied based on that.

- Application of those alternative fuels and mix more than one material if needed, in a real-world energy-intensive industry like cement industry and studying the environmental and economic impacts of using those materials compared with fossil fuels.

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