A Review on Green Wastes Pyrolysis for Energy Recovery

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Abstract: - Pyrolysis has a long history as a thermo-chemical conversion process to convert biomass to bio-fuels. It has large future potential driven by increased interest in renewable energy sector. Biomass supplies about 14% of the world's total energy needs. The pyrolysis product such as bio-oil, charcoal and gaseous products have multi-dimensional uses. Bio-oil can be suitable substitute for fuel oil or diesel fuel in many static applications including boilers, furnaces, engines and turbines for electricity generation. Pyrolysis gas and charcoal contains significant thermodynamic properties for heat and power generation in various types of industries. Council green waste, one of the sources of renewable energy, has a positive environmental impact resulting in no net releases of carbon dioxide and very low sulphur content. Pyrolysis process can successfully be applied for converting council green waste into bio-energy. Recent progress in green waste pyrolysis is elaborated and discussed in this paper. The sustainability of bio-fuel generation using pyrolysis, uses and applications of pyrolysis products, environmental impacts of pyrolysis process and recent progress in pyrolysis process modelling and simulation are also presented and discussed in this paper.

Keywords: Pyrolysis, Bio-oil, biomass, Green waste, bio-fuels, bio-energy.

1. Introduction

There is widespread recognition of the positive contribution that renewable energy can make to reduce greenhouse gas emission by substituting fossil fuels in energy production. Biomass can be used for energy production in several ways from direct burning to gasification and pyrolysis. Asadullah et al. [1] found that, by the direct combustion the biomass is completely transformed into heat but only 10%-15% is effectively heated the target matter. Goyal et al. [2] said that, biomass can be converted to useful products by two main processes - Thermo-chemical processes and Bio-chemical processes. Different thermo-chemical conversion processes that include combustion, gasification, liquefaction, hydrogenation and pyrolysis can convert the biomass into various energy products. Broadly, the thermo-chemical conversion processes have two basic approaches. The first is the gasification of biomass and its conversion to hydrocarbons. The second approach is to liquefy biomass directly by pyrolysis. Pyrolysis converts the waste biomass into energy rich useful products. Choice of conversion process depends on the type and quantity of biomass feedstock, the desired form of energy, end user requirements, environmental standards, economic conditions and project specific factors.

Among the biomass to energy conversion processes, pyrolysis has attracted more interest in producing liquid fuel product because of its advantages in storage, transport and versatility in application such as combustion engines, boilers, turbines, etc. In addition, solid biomass and waste are very difficult and costly to manage which also gives impetus to pyrolysis research. However, it needs to overcome a number of technical and economic barriers to compete with traditional fossil fuel [3, 4]. The production of bio-liquids and other products (char and gas) by pyrolysis of different biomass species has been extensively investigated in the past. Some of this biomass variety includes beech wood [5], bagasse [6] woody biomass [7, 8], straws [9], seedcakes [10], municipal solid waste (MSW) [11'12].

The utilization of biomass has a lot of advantages such as: i) It minimises environmental air pollution, ii) It is sustainable and abundant availability, iii) No sulphur emission and mitigate acid rain, iv) Maintains carbon neutrality in atmosphere and v) Lower NO_x emission in the nature vi) Bio fuel's co-product can be used as soil additives. Berndes et al. [13] said that in 2003, biomass share in the world's total primary energy consumption was about 12%. Biomass is recognised as a renewable resource for energy production and is abundantly available around the world [14]. Utilisation of biomass in mainstream energy uses is receiving great attention due to environmental considerations and the increasing demands of energy worldwide [15]. In addition, zero or negative

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carbon dioxide (CO_2) emission is possible from biomass fuel combustion because released CO_2 from the combustion of bio-oil can be recycled into the plant by photosynthesis [16].

Biomass is defined as anything biological material from living or recently living organisms' on earth. These are the substances in which solar energy is stored. Plants generate biomass continuously by the process of photosynthesis [17]. The biomass sources include bagasse, pulping liquor from paper production, forestry residues and wood processing residues, energy crops, crop residues and wet wastes from agriculture and food processing. Demirbas [18] stated that, biomass resources can be divided into two broad categories, i.e., natural and derived materials and subdivided into three categories such as wastes, forest products and energy crops. Green waste from the municipal councils can be considered as one of the major world renewable energy sources to supplement declining fossil fuel resources. Green waste can be sustainably developed in the future and has a positive environmental property resulting in no net releases of carbon dioxide and very low sulphur content. Moreover, green waste appears to have significant economic potential provided that fossil fuel prices increase in the future. Pyrolysis is the significant and flexible way to take care of green waste. Although thermo-chemical biomass conversion is not a new technology, Pyrolysis is not yet widely used. There is very limited information available in the literature for using municipal green waste for bio-fuel production. By displacing fossil fuel, green waste pyrolysis helps to meet green energy target, lessen environmental effects on climate change, global warming and contribute to achieving Kyoto Protocol. In this paper green waste source, different disposal process, energy values, pyrolysis system, pyrolysis product characteristics, uses and applications, recent progress in modelling and simulation and environmental impact of pyrolysis are presented and discussed.

2. Green Waste

Basically the "Green waste" is produced from regular maintenance of gardens and parks. It consists of all plant materials: branches, logs, leaves, stumps, grass, sticks, paper, cardboard, and other woody materials. It also contains large quantities of waste paper and cardboard, waste timber, old wooden pallets and sawmills wastes. These wastes as well as other wood wastes are usually dumped in the landfills. The largest single component of municipal waste is green waste and traditionally it takes up a significant quantity of landfill volumes. All of those wastes are suitable for charcoal and energy production.

2.1 Green Waste Disposal

Green waste can be disposed in many ways: Burying in landfills, using as mulch, composting and then used in crop production, vermicomposting and used in plant production, used as a landscape mix in landscaping, bio-char and bio-oil preparation (pyrolysis), used as a feedstock in electricity generation, used as a feedstock in bio-tar synthesis. Landfill disposal has no significant benefits; it is neither economical nor environmentally favourable. These wastes could potentially serve as a fuel and produce valuable products. Green wastes in landfill decompose to produce methane and carbon dioxide. If released to the atmosphere, these gases would cause a greenhouse impact equivalent to about 100,000 tonnes of carbon dioxide per year in Australia [20]. Alternatively, producing energy from these wastes, thereby replacing the burning of fossil fuels, could reduce emissions of carbon dioxide by about 22,000 tonnes a year [21]. Although a significant portion of solid green waste (SGW) is used in landscaping, it is not possible to use all of the SGW for landscaping. Therefore, the Council needs to store and manage the surplus SGW though it is expensive and risky.

2.2 The Energy Values of Green Wastes

Green waste represents a renewable and sustainable source of energy. The average majority of biomass energy is produced from green wastes (64%), followed by solid waste (24%), agricultural waste (5%) and landfill gases (5%) [19]. In the case of energy application without chemical processing, green waste (biomass) is combusted. During combustion energy conversion from green waste may be effected by thermo-chemical, biological or chemical processes. These may be categorized as: direct combustion, pyrolysis, gasification, liquefaction, super critic fluid extraction, anaerobic digestion, fermentation, acid hydrolysis, enzyme hydrolysis, and esterification. Significant chemical properties for green waste combustion are the elemental analysis, proximate analysis, analysis of pyrolysis products, higher heating value, heat of pyrolysis, heating value of the volatiles, and heating value of the char. Some properties vary with species, location within the biomass fuels, and growth conditions and other properties depend on

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the combustion environment. Presence of higher moisture content and high O_2 content causes significantly lower heating value than other fossil fuels. It can be comprehend that lower heating values lead to lower flame temperatures. Table 1 shows the physical, chemical and fuel typical properties of biomass and coal fuels.

Table 1: Physical, chemical and fuel properties of biomass and coal fuels [22]

Property	Green Waste	Coal
Fuel density (kg/m^3)	~ 500	~1300
Particle size (mm)	~ 3	~ 100
C content (wt% of dry fuel)	42–54	65–85
O content (wt% of dry fuel)	35–45	2–15
S content (wt% of dry fuel)	Max 0.5	0.5–7.5
Ignation temperature (K)	418–426	490–595
Peak temperature (K)	560–575	--
Friability	Low	High
Dry heating value (MJ/kg)	14–21	23–28

Green waste decomposition can be characterised by (a) particle size and specific gravity, b) ash content, (c) moisture content, (d) extractive content, (f) element (C, H, O and N) content, and (g) structural constituent (cellulose, hemicelluloses and lignin) content. The presence of inorganic compounds favours the formation of char [21]. Ash content is an important parameter which directly affects the heating value. Moisture decreases its heating value. Presence of organic components or extractives also impacts on heat content in green waste. Extractive content is important parameter which raises the higher heating values of the wood fuels.

3 Green waste Pyrolysis

Pyrolsis is a thermo-chemical decomposition process which is found to be the best suited for conversion of biomass to carbon-rich solid and liquid fuel. By this process biomass is thermally destructed in the absence of oxygen. Pyrolysis of biomass starts at 350–550 ^{0}C and goes up to 700 ^{0}C. By this technology different operating condition leads different proportions of products formation. Production of bio-oil and biochar by using Pyrolysis principle is practical, effective, and environmentally sustainable means of generating large quantities of renewable bio energy while simultaneously reducing emissions of greenhouse gases. The process is represented simply by equation given in Figure 1. Pyrolysis process can easily be differentiated from gasification; in gasification biomass decomposes to syngas by controlling the presence of oxygen. In early stages pyrolysis is only used for solid char production, but today the term pyrolysis describes processes in which oils are the most preferred products.

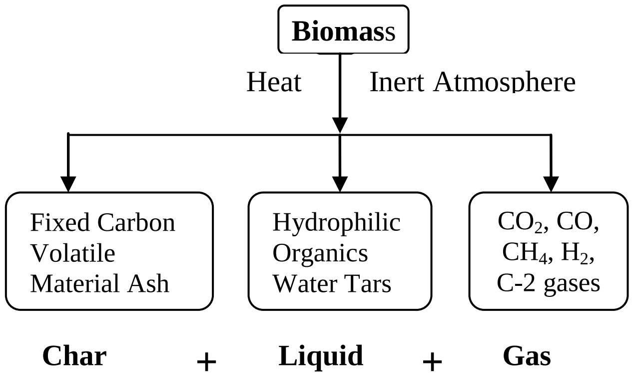

Figure 1: Pyrolysis process equation

Nowadays there are mainly three ways frequently used to extract energy from biomass. These are: Combustion (exothermic), Gasification (exothermic) and Pyrolysis (endothermic) mentioned by Frassoldati *et al.* [24]. During the Combustion process biomass can be completely oxidised and transferred into heat. According to Pei-dong *et al*, [25] and Thornley *et al*. [26] efficiency of this process is only about 10 percent and this manner of use is a source of substantial pollution. Gasification is a partly oxidizing process that converts a solid fuel into a gaseous fuel, while pyrolysis is the first stage of both combustion and gasification processes observed by Rowell [27]. Therefore pyrolysis is not only an independent conversion technology, but also a part of gasification and combustion process said Grønli *et al*. [28] which consist of a thermal humiliation of the biomass into gases and liquids without an oxidising agent.

The process of pyrolysis of organic matter is very complex and consists of both simultaneous and successive reactions when organic material is heated in a non-reactive atmosphere. In this process, thermal decomposition of organic components in biomass starts at 350–550 ^{0}C and goes up to 700-800 ^{0}C in the absence of air/oxygen suggested by Fisher *et al*. [29]. The long chains of carbon, hydrogen and oxygen compounds in biomass break down into smaller molecules, in the form of gases, condensable vapours (tars and oils), and solid charcoal under pyrolysis conditions. Rate and amount of decomposition gases, tars and char depends on the process parameters of the reactor (pyrolysis) temperature, heating rate, pressure, reactor configuration, feedstock's variation. Figure 2 shows schematic diagram for fast pyrolysis processes [30].

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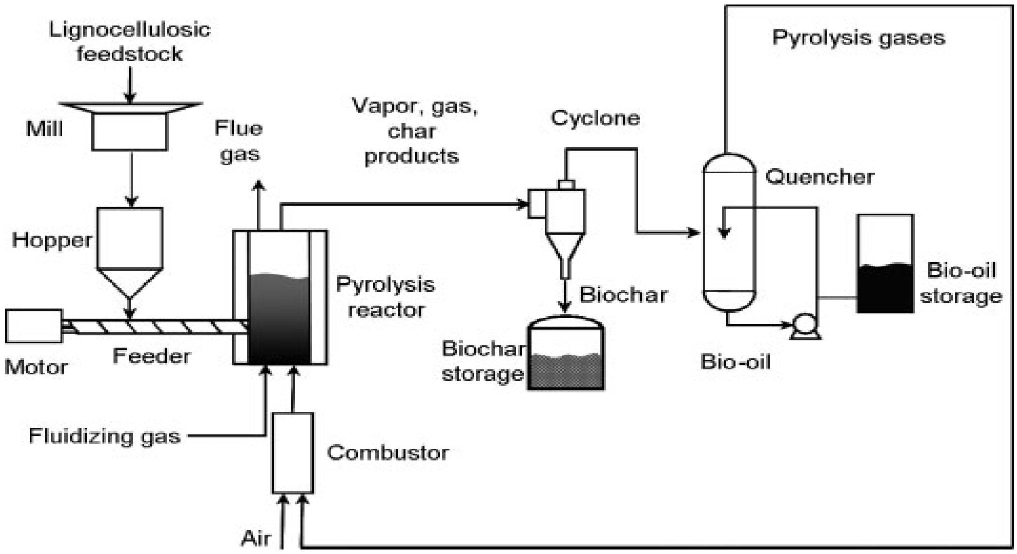

Figure 2: Schematic diagram showing fluid bed pyrolysis processes.

3.1 Pyrolysis Process steps

Pyrolysis process is a combination of some steps. All the steps simply categorise as feed stock preparation, Feed stock drying, thermo-chemical conversion in the reactor, ash separation and liquid collection. Different reactor needs different sizes particle, that is why cutting and grinding is needed. Drying is essential to avoid adverse effects of water on stability, viscosity, corrosiveness and other liquid properties in the pyrolysis product. After drying and grinding, the biomass is fed into the reactor and the pyrolysis process takes place. Char removal cyclones are used to separate char. Pyrolysis liquid is collected after quenching the volatile material by the vapours liquid condensers.

3.2 Pyrolysis oil Characteristics and Comparison

Pyrolysis oils, usually referred as bio-oil have limitations in fuel quality, phase separation, stability, fouling issues on thermal processing and economic viability. It consists of about 300 to 400 compounds [31]. Studies found that the reactions and aging effects occur faster at higher temperatures but the effects can be reduced if the pyrolysis oil is stored in a cool place [32, 33]. Pyrolysis oil yields, quality and stability can also be tailored by process variables such as heating rate, pyrolysis temperature, residence times, quenching time, method of oil collection etc. Some physical properties of bio-oil are shown in Table 2.

Table 2: Typical physical Properties of Pyrolysis Bio-oil and Heavy oil [8, 30]

Physical property	**Bio-oil**	**Heavy fuel oil**
Moisture content (wt %)	15-30	0.1
pH	2.5	
specific gravity	1.2	0.94
Ash	0-0.2	0.1
HHV (MJ/kg)	16-19	40
Viscosity(centistokes) at 50 ^{0}C	7	50
Pour point(^{0}C)	- 33	- 18

3.3 Uses and Applications of pyrolysis products

Depending on feedstock characteristics, the Fast pyrolysis can produce 60-75 wt % of liquid bio-oil, 15-25 wt % of solid char, and 10-20 wt % of non-condensable gases. According to Bridgwater *et al.* [34] fast pyrolysis processes are designed and operated to maximise the liquid fraction at up to 75% wt on a dry biomass feed basis. Cottam [35] mentioned that, char may be sold or used internally to provide heat for the process. Pyrolysis gas has a medium heating value and can be used internally to provide process heat, re-circulated as an inert carrier gas or exported for feed drying. Velden *et al.* [36] showed through lab-scale batch experiments and pilot scale circulating fluidised bed experiment that fast pyrolysis can produce 60 to 70 wt% of bio-oil at an operating temperature varied from 490 to 510 ^{0}C. Interestingly no waste is generated, because the bio-oil and solid char each can be used as a fuel and the gas can be recycled back into the process. Liquid

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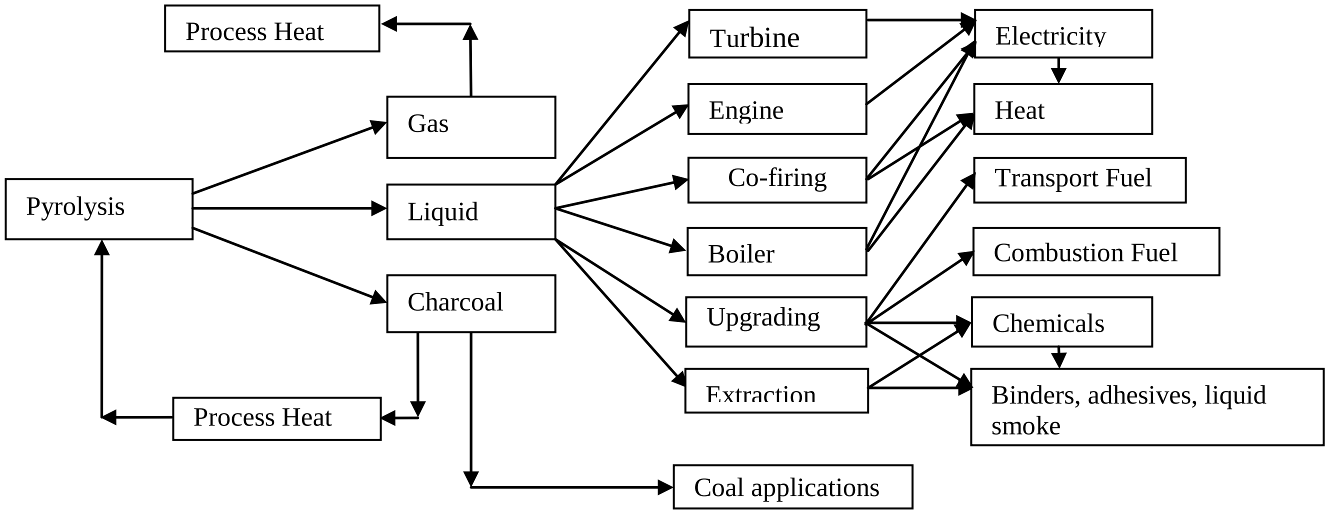

Figure 3: Applications of Pyrolysis Products.

products can be easily and economically transported and stored, thereby de-coupling the handling of solid biomass from utilisation [37]. The basic characteristics of the fast pyrolysis process are high heat transfer and heating rate, very short vapour residence time, rapid cooling of vapours and aerosol for high bio-oil yield and precision control of reaction temperature [38]. Various applications of pyrolysis products are shown in Figure 3.

3.4 Recent Progress in Pyrolysis Modelling and Simulation

According to Prakash and Karunanithi [39] the modelling of pyrolysis was started during 1940's and gradual changes and improvements have been made until to date. From all previous works various modelling approach, kinetic schemes, numerical analysis method were proposed. The decomposition of wood and woody material through pyrolysis process involves with a complex series of reactions and consequently changes with experimental heating conditions, method of sample preparation, temperature, thermodynamic properties, particle physical properties and moisture content. Considering all these it is necessary and required to do more research for further improvement and enrichment in the modelling and simulation in this sector. A summary of recent modelling and simulation work is presented in Table 3.

The modelling of pyrolysis has a wide range of approach with varying complexity. Wood and woody material have compound chemical composition, structural variation, heating rate effect, residence time effect which results secondary reactions. Least number of pyrolysis works has been done with realistic pyrolysis reactor model. Close co-operation is needed between manufacturer and researcher for design and modelling of pyrolysis process. For modelling and simulation purposes Advanced System for Process Engineering Plus (ASPEN Plus) software package is a complete integrated solution for process engineering including reactor. It has no built in models but Aspen Plus software can easily calculate the pyrolysis yield and optimizing the operating conditions by getting chemical properties from ultimate analysis test values.

Table 3: A list of Modelling of Pyrolysis process

Researcher	Contribution
Luo *et al.* [40]	Proposed model combined reaction kinetics with mass and heat transfer to predict pyrolysis behaviour in a fluidized bed reactor
Ravi *et al.* [41]	Semi-empirical model for pyrolysis of sawdust in an annular packed bed.
Yuen *et al.*,[42]	Pyrolysis model for three-dimensional formulation and analysis of wet wood
Yuen *et al.* [43]	Extended previously developed 3-D pyrolysis model by Yuen *et al.* [42]
Boateng & Mtui [44]	CFD modelling of space-time evolution in a bench-scale fluidized-bed reactor
Yan and Zhang [45]	An ASPEN PLUS based simulation model has been developed for a low temperature coal pyrolysis process.

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3.5 Environmental Impacts of Bio-energy

The contamination of air by the discharge of harmful substances in the atmosphere causes injury or tends to be injurious to human health or welfare animal or plant life. Air pollution has caused thinning of the protective ozone layer of the atmosphere, which is leading to climate change [46].The use of biomass energy has many unique qualities, environmental benefit is one of the most important one. Demirbas [46] addressed that, it can help mitigate climate change, reduce acid rain, soil erosion, water pollution and pressure on landfills, provide wildlife habitat and help maintain forest health through better management. Demirbas [46] also said that about 98% of carbon emissions result from fossil fuel (coal, oil and natural gas) combustion. Biomass energy recovery technologies have advanced to be largely pollution free. There is zero to little production of slag, ash, SO_x, NO_x, or CO_2 in biomass consumption [47]. Biomass is very reliable with environmental protection policies. Combustion of wood results in lower emissions of SO_2 and alleviates the chance of acid rain.

4. Conclusions

Energy recovery from green waste through pyrolysis process has been discussed in this paper. Pyrolysis technology has strong adaptability to green waste to produce liquid fuels with high bio-oil yields. It offers a convenient solution for municipal waste management systems. In spite of comparatively low-grade bio-fuels obtained from biomass; it has some promising properties to become a suitable substitute of fossil fuel. In future successful research and improvement of bio-fuel quality can lead to huge production of bio-energy from green waste commercially. It is important to optimise the process by maximising product quality and quantity while paying proper attention to minimising costs and environmental concerns. Currently, authors at Central Queensland University, Australia, are developing a computational model of green waste pyrolysis process using Aspen Plus process engineering software in order to analyse pyrolysis performance and to optimise process for maximising the yield.

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