Pyrolysis Technology

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Pyrolysis technology is a thermo-chemical route for converting biomass to many useful products (biochar, bio-oil, and combustible pyrolysis gases). The composition and relative product yield depend on the pyrolysis technology adopted.

Keywords: pyrolysis ; pyrolyzers ; fast pyrolysis ; slow pyrolysis ; advanced pyrolysis

1. Introduction

Pyrolysis is an established thermochemical process for converting biomass materials into bio-oil, gaseous products, and liquid fuel. The process can be categorized into slow, fast, and flash pyrolysis [1]. Each pyrolysis type has different products and their corresponding compositions [2].

Pyrolysis occurs in an inert atmosphere by applying thermal heat to change biomass into numerous fuels, such as char, gas, and liquid oils. The liquid fuel is a combination of dozens of oxygenated organic compounds [3]. Multiple products are formed depending on the various operation conditions, such as the rate of heating, operating temperature, residence time, and biomass particle size [4]. The amounts of lignin, cellulose, and hemicellulose, which are leading polymers of biomass, also contribute to the composition of the final products [5]. Compared to thermochemical conversion processes, such as combustion and gasification, pyrolysis occurs at moderately lower temperatures (400–600 °C) and is generally preferable because the pyrolysis products, mainly char and liquid fuels, are easy to store and transport [6].

Considerable research has been conducted into the pyrolysis of different materials, including biomass and, most recently, e-waste materials such as electronics scrap components. Pyrolysis has numerous advantages as compared to other thermochemical conversion processes, such as [7]:

1. It is a simpler and relatively cheaper conversion process.Pyrolysis efficiency is the thermal efficiency obtained as the
2. Pyrolysis is suitable for a wider variety of feedstock.ratio of the difference between the overall heating values of the
3. It reduces the landfill requirements and greenhouse gas (GHG) emissions.pyrolytic products and the total thermal
4. It has very little water pollution potential.energy utilized for processing the sample. Pyrolysis is a well-known process of
5. Pyrolysis reactor construction is relatively rapid process.producing high energy-density biofuels and chemicals [8]. Wang et al. [9] presented a comprehensive overview of the pyrolysis mechanisms of three biopolymers in biomass materials and highlighted the complexities in their structure. Sharma et al. [10] conducted a critical review of pyrolysis modeling to highlight the gaps in the technology and explore new opportunities for integrating biomass pyrolysis models of disparate scales. Kan et al. [11] published a comprehensive review of the pyrolysis product properties and effects of pyrolysis parameters. They reported that the heating rate and temperature are the main influential parameters affecting the pyrolysis yield and quality. Dai et al. [12] published a review on understanding the chemistry of non-catalytic and catalytic pyrolysis processes. They introduced recent progress on producing value-added hydrocarbons, phenols, anhydrosugars, and nitrogen-containing compounds from the catalytic pyrolysis of biomass over zeolites and metal oxides via different reaction pathways. The pyrolyzer reactor in the biomass pyrolysis process is the primary component used to convert biomass into valuable products. Several review papers on the biomass pyrolysis process are available, but the authors found few studies on the scope of biomass pyrolyzers. Most review papers on biomass pyrolysis presented experimental and modeling studies in general. Few articles explained the characterization of the products (bio-oil and bio-char). There are also review papers available on the pyrolysis process parameters, the catalyst used in the reactions, and the upgradation of products. Garcia-Nunez [13] presented a study of different reactors used in biomass pyrolysis, and the review paper presented the pyrolysis technologies from a historical perspective.

2. Future Perspective and Commercialization of Pyrolysis Technology

The pyrolysis economics and environmental constraints will be optimized further to produce more valuable products and enhanced pyrolysis process efficiencies. Pyrolysis production technology towards more demanding products and increasing process efficiencies have been linked mainly to the reactor configuration and feedstock logistics [14]. Another way to fulfill this goal is to use different catalysts to maximize the conversions and improve the yield quality [15]. Another emerging solution to add more value to the pyrolysis technology products is converting bio-oil into crude oil. Crude oil is in much more demand and can be integrated easily into the present commercial fuel market. Similarly, bio-oil to transportation fuel is another research area that can help expand the scope of pyrolysis products [16]. Some models have been presented and tested to overcome the issues related to feedstock logistics. For example, mobile pyrolysis units near the feedstock location eliminate feedstock handling and transportation charges. With this arrangement, multiple feedstocks can be processed [17]. On the other hand, the fruitful results depend mainly on the suitable selection and configuration of the pyrolysis reactor. Not all feedstock materials can be processed with the same pyrolysis technology. The desired product and yield can determine the correct choice of pyrolysis technique that needs to be adopted. The following research areas need to be considered to improve the pyrolysis reactor configuration further [18][19]:

1. Pyrolysis reactors should be efficient and effective in heat transfer,
2. Should speed up the reactivity of pyrolysis,
3. Produce bio-oil with a lower molecular weight,
4. Pyrolysis products should have zero toxicity,
5. Thermally stable pyrolysis reactors,
6. Less ash agglomeration in reactor beds, and
7. Should have good control over temperature and heating rates.

The magnitude of greenhouse gases (GHG) released from the pyrolysis processes is very small compared to conventional fuels. Nevertheless, there is a research scope to expand the environmental benefits further because pyrolysis is an emerging technology with the benefits of using multiple feedstocks [20]. Above all, the most valuable benefit is the production of a wide range of fuels. Hence, a comprehensive assessment of the pyrolysis process is required to highlight the gaps and direct the research in potential progress areas. **Table 1** presents an overview of the life cycle global warming potential (GWP) for various feedstock. GWP is the best approach for analyzing the effects of pyrolysis on the environment and its contribution to global warming. The positive and negative values of GWP represent the increase and decrease in emissions, respectively. Biochar used for soil remediation has better global warming potential than using pyrolysis products for energy applications. **Table 2** lists some commercially installed pyrolysis reactors.

Table 1. Life cycle global warming potential (GWP) of some pyrolysis products.

Feedstock	Reactor	Plant Capacity Ton/Year	Product Yield L/DT	Application	GWP	Ref.
Corn stover	**Rotary kiln**	**84,000**	**-**	**Soil amendment**	**−865**	[21]
Barley straw	**Rotary kiln**	**100,000**	**-**	**Soil amendment**	**−900**	[22]
Sewage sludge	**-**	**2000**	**-**	**Energy generation**	**−750**	[23]
Poplar wood	**Fluidized bed**	**-**	**300**	**Gasoline and diesel**	**0.74**	[24]
Forest residue	**Hydroprocessing**	**-**	**350**	**Gasoline**	**1.21**	[25]
Forest residue	**Fluidized bed**	**-**	**114**	**Chemicals**	**−0.53**	[26]
Wood residue	**Fluidized bed**	**-**	**320**	**Bio-oil**	**0.11**	[27]

Table 2. Some commercially installed pyrolysis reactors.

Technology	Location	No. of Units	Max. Size Kg/h
[a] Fixed-bed and moving-bed	**Anhui Yineng Bioenergy Ltd., China**	**3**	**600**
[a] Vacuum pyrolysis	**Pyrovac, Canada**	**1**	**3500**
[a] Ablative reactor	**PyTec, Germany**	**2**	**250**
[a] Rotating cone	**BTG, Netherlands**	**4**	**2000**
[a] Circulating fluidized bed	**Metso/UPM, Finland**	**1**	**400**
[a] Fluidized-bed	**RTI, Canada**	**5**	**20**
[b] Transported fluidized-bed	**Ensyn, Canada**	**8**	**4000**
[b] Bubbling fluidized-bed	**Dynamotive, Canada**	**1**	**3800**
[b] Indirect heating rotary kiln	**Mitsubishi Heavy Industries**	**1**	**4000**

Technology	Location	No. of Units	Max. Size Kg/h
[b] Rotary cone	BTG, Malaysia	1	2000
[b] Heated kiln pyrolysis followed by gasification	Choren, Germany	1	6800
[c] Fluidized bed	Phrae, Thailand	1	10–20

a = [28], b = [11], c = [29].

3. Conclusions

Pyrolysis is a promising technology for altering biomass into more valuable renewable energy. The process can deliver sustainable and green energy to meet domestic, industrial, and commercial needs. This review conveys a summary of current efforts and developments as well as the environmental and economic features of this energy conversion technology. In pyrolysis, less-valued biomass material is transformed into high-value biochar, bio-oil, and combustible gases. The perspective to decrease the growth of greenhouse gases (GHG) from pyrolysis depends on several factors, such as the type of biomass feedstock used, type of pyrolysis conversion technology, the scope of the pyrolysis unit, and the way co-products are recycled. Slow pyrolysis can deliver superior ecological outcomes as it yields additional biochar that can be applied to soil to sequester carbon. Fast pyrolysis has financial benefits through the production of bio-oil, which is a higher-value product. Advanced pyrolysis processes can also provide high welfare for specific applications. The success of pyrolysis can be determined by the biomass feedstock prices, product yields, aptitude to produce advanced value products, and production balance. **Table 3** summarizes the detailed advantages and disadvantages of different pyrolysis reactors. Furthermore, the current review paper also highlights important research gaps in the pyrolysis process using different types of pyrolyzers. The implementation of artificial intelligence will be a breakthrough in the field of the pyrolysis process. Hybrid energy systems using biomass pyrolysis processes with other renewable energy sources are needed to explore cost-effective and energy-efficient processes. The integration of pyrolysis reactors with other biomass conversion technologies can help enhance the product yields.

Table 3. Advantages, disadvantages, and bio-oil yield range of various pyrolysis reactors.

Reactor Type	Advantages	Disadvantages	Oil Yield
Fixed-bed	Simple and reliable design Biomass size dependent	Long residence time Difficult to remove char	35–50%
Bubbling fluidized-bed	Simple design and easy operation Suitable for large scale	Small particle sizes are needed	70–75%
Circulating fluidized-bed	Good temp. control Large particle size could be used	Suitable for small scale Complex hydrodynamics	70–75%
Rotating cone	No carrier gas required Less wear	Complex process Small particle	65%
Vacuum	Produce clean oil Can process large particle (3–5 cm) No carrier gas required	Slow process Solid residence time is too high	65%
Ablative	Inert gas is not required Large particle sizes can be processed	Reactor is costly Low reaction rate	70%
PyRos	Compact and low cost High heat transfer Short gas residence time	Complex design High impurities in the oil High temp. required	70–75%
Microwave	High heating rates Large size biomass can be processed High temperature	High electrical power consumption High operating costs	60–70%

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