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Biomass Conversion For The Production Of Fuels: A Brief Study.

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Abstract

By thermochemical process, pyrolysis of biomass which is present in organic matter takes place in the absence of oxygen to develop a sustainable route for converting biomass into bio-fuel. Biomass is a promising source of energy for producing either solid or liquid fuels. Biofuels are alternatives to fossil fuels to reduce greenhouse gas emissions. This review provides a overview of biomass pyrolysis, discussion upon its fundamental principles and its applications at various industries. The bio-oil can be obtained from agricultural waste, forest residue, and urban organic waste. It is also called pyrolysis oil, renewable fuel, and has the potential to be used as fuel in many applications. The application of bio-oil as transportation fuel helps to reduce the emission of greenhouse gases and to keep up the ecological balance. It covers major pyrolysis types and explores the reactors used in these processes and how key parameters, such as temperature, heating rate, and residence time, impact the distribution and quality of pyrolysis products. Nowadays biomass is becoming a booming industry because it is cheaper and are effective for the sustainable use. Detailed studies are performed about bio-oil upgrading methods such as catalytic and non-catalytic processes. Several studies present techno-economic assessments of different routes regarding cost-effective configurations. The advancements which are achieved to large production of bio-oil continues to face different challenges and variability in supply of feedstock. This review explains the usefulness of reactor design, catalyst efficiency, and optimization of process along with commercial deployment. Finally, this review is much helpful to researchers and engineers, to work together about advance pyrolysis technology to provide low carbon fuels and chemicals for the society.

Keywords: biomass; pyrolysis; reactors; bio-oil upgrading; economic analysis

1. Introduction

It is observed that demand of approximately 40% of global energy in future could be fulfilled by biomass-based energy [1]. It is not acceptable to substitute fossil fuels with the sustainable energy sources. Therefore, utilization of biomass for the production of fuel and chemicals is necessary. Significantly, uses of biomass to produce liquid fuels has achieved interest [2].

It is important to understand biomass and its conversion options for the potential of biomass. It consists of organic, biological and other substances obtained from living organisms through various processing methods [3, 35]. Global population growth and increasing energy demand are creating pressure on existing energy systems for the need to consider renewable and sustainable energy sources. [4]. It can be classified into agricultural, wood-based, industrial wastes, food waste, animal waste and human wastes. Biomass can be converted into biofuels using either biological or thermal processes. The biological conversion of biomass to fuel totally depends upon the food based raw material at commercial level. [5, 47]. And, the thermal conversion can process a vast raw material in short residence time and can handle complex biofuels also. Pyrolysis is one of the most effective and versatile thermal conversion methods. pyrolysis is suitable to produce liquid fuels and chemicals for refining into transportation fuels. The process in which to handle heterogeneous feedstocks and at moderate scales makes it helpful for energy systems and rural deployment [6]. But still biomass pyrolysis is not a mainstream commercial process because of variability fuel quality, limited catalyst lifetimes and cost-effective reactors [7].

This review covers principles and mechanisms of pyrolysis, various types of pyrolysis, various reactors, fuel upgrading techniques, economy of various processes and global biomass companies contributing to the development of pyrolysis technologies. [36]

2. Process of Biomass Conversion

The conversion of biomass mainly shows following steps. (A) Evaporation of free moisture from the biomass. (B) Decomposition of the biomass at temperature between 200 and 400 ˚C to form solid char after degradation of biomass (C) Reactions: these include oil cracking and repolymerization, taking place within the solid material. Biomass is mainly composed of three components namely cellulose, hemi- cellulose and lignin. Some little quantity of extractives and ash is also present. [46]

The decomposition of cellulose is the most studied following the Waterloo mechanism, which involves dehydrogenation, depolymerization, and fragmentation process at different temperatures [8]. In addition to the main components, ash can affect the biomass breakdown during pyrolysis. The amount and type of ash can change the speed of reaction, formation of products and quality of product. Higher ash content tends to lower the yields bio-oil. Potassium and some other minerals which are present in ash can promote different breakdown reactions. [9, 54].

Characteristically pyrolysis of organic materials proceeds through three distinct phases. The gaseous phase mainly consists of carbon monoxide (CO) and hydrogen (H_2). The process produces solid by-product, commonly referred to as char. This solid fraction may also contain aromatic compounds as a minor contaminant. At high temperatures this process produces solid carbon residue, it is termed as carbonization. [10, 42].

3. Types of Reactors

The reactors used for biomass pyrolysis are important factor for pyrolysis process because reactors mainly determine quality, quantity, properties, and characteristics of the products [11, 33]. Various types of reactors have been developed to optimize production of fuel and composition.

3.1 Microwave Reactors

Microwave reactors represent a recent advancement in biomass pyrolysis. It offers several advantages over traditional slow pyrolysis reactors. The drying process in microwave reactor occurs in an oven chamber, while an inert gas is used to maintain an oxygen-free environment inside the reactor. Energy transfer occurs by the interactions between molecules and atoms, which results in efficient heat transfer. Zhao et al. [12, 41] reported the impact of microwave heating on biomass pyrolysis and represents that higher temperatures influenced the process, increasing the proportion of the combustible gases and enhancing bio solid. [45]

3.2 Fixed-Bed Reactors

Typically, Fixed-bed reactors are constructed from firebricks or steel and contain different parts such as, a feeding unit, cooling system, ash cleaning unit, and gas exit. These reactors are characterized by long biomass residence time, high carbon conservation, reduced ash release and low gas velocity. These are commonly usefull in small-scale energy generation systems. Messina et al. [13] reported pyrolysis of acid-treated peanut shells at various temperatures. They found that the optimal temperature at 500 ˚C. Production of 42% fuel from treated biomass as compared to 33% from untreated biomass has been observed.[53]

3.3 Auger Reactor (Screw Reactor)

Auger reactor works by mixing feedstock with hot sand using a screw conveyor to control reaction times. The main advantages of this kind of reactor are low operating temperatures and the ability to use small reactor sizes. [44] On the other hand, the drawbacks of this reactor are long vapor residence times which results in lower production of pyrosis oil and mechanical unreliability because of exposure of moving parts at high temperatures. Papari et al. [14] conducted a study using an Auger reactor for bio-oil production by using forest residues which achieved a 53% oil yield at 450–475 ˚C. [52]

3.4 Ablative Reactors

Ablative reactors are much complex systems that are used for biomass pyrolysis and characterized by intense and mechanically driven processes. Heat is transferred from the ablative reactor walls to the biomass particles under pressure, which removes volatiles substances very fast. It operates at temperatures around 600 ˚C, achieving high particle velocity.[49] Vacuum ablative pyrolysis of tobacco residues was performed to generate bio-oils. The effects of reaction temperature, particle size, and rotation speed on the pyrolytic products were considered and production of 55% w/w bio-oil at 600℃ takes place with particle size of 1 cm. The bio-oil obtained was of good quality with high carbon and hydrogen contents and high calorific value. [15, 34] The advantages of this reactor are high heating rates, efficient heat transfer, energy and cost efficiency and compact design.

3.5 Free-Fall Reactor

Free-fall or drop-tube reactors represents a simple and effective technology for the pyrosis of biomass. During bio-oil production using free-fall reactors, the particles descend through the length of the free-fall reactor. Since the biomass is introduced from the uppermost region of the reactor, the flow of gaseous products is diminished relative to other reactor types. [16] Char is trapped in a collector while the volatile gas removes solid particles by creating cyclone prior to entering a condenser. Furthermore, bio-oil is recovered by quenching volatile gases. [37, 43]

4. Upgradation of Fuel

It is necessary to do upgradation of bio-fuels to enhance its stability, increase its heating value, reduce char and ash contents, lower viscosity and acidity, and improve its suitability for blending with fossil fuels [3].

4.1 Solvent addition

Using polar solvents like acetone, ethyl acetate, methanol and ethanol has been a long-standing practice to improve homogenization and reduce the viscosity of biomass derived oils [17, 48]. The introduction of solvents to bio-oil serves a dual purpose in viscosity reduction. Firstly, it physically dilutes the bio-oil, directly decreasing its viscosity. And secondly, it initiates chemical interactions between the solvent molecules and bio-oil constituents.[38] The addition of alcohol improves the homogeneity of the bio-oil by preventing the phase separation. The raw bio-oil having some soluble hydrophobic compounds. By adding alcohol, the solubility of those hydrophobic compounds increased and it leads to separate from the bio-oil [18].

4.2 Esterification

In bio-fuel production, esterification converts free fatty acids into alkyl esters. This involves the reaction of fatty acids with alcohols in the presence of an acid catalyst at atmospheric pressure. Methanol is frequently employed as the solvent because it is cost effective and easy to handle [19]. Peng et al. [20] found that catalytic upgrading of bio-oil using ethanol is more effective. Water is a by-product of esterification and its removal can increase reaction yield. [21].

4.3 Supercritical Fluids (SCFs)

A liquid becomes a supercritical fluid at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist. Xu et al. [22] have shown that using SCFs, such as 1-butanol or water with catalysts, results in bio-oil with good properties compared to non- supercritical conditions. Making them comparable to petroleum-based fuels.

4.4 Catalytic Cracking

Zeolites are commonly employed as catalysts and adsorbents due to their high surface areas and adsorption capacities. Zeolite cracking which is a bio-oil upgrading technique performed at 350–500 ˚C, involves deoxygenation and produces gases like CO_2, CO, and light alkanes, water soluble organic substances, oil-soluble organic substances and coke [23, 32]. Mortensen et al. [24] presented experiments to compare zeolite cracking and hydrodeoxygenation methods for bio-oil upgradation.

5. Economy

This study helps to quantify the capital and operating costs, evaluate profitability, and assess long-term viability under different configurations, scales, and feedstocks. Economic analysis helps to serves as a tool for guiding investment decisions and public policy aimed for the production of the low-carbon fuels. According to Wright et al. [25, 30], economic analysis is required for understanding cost structures and also for identifying improvements of processes and supporting commercialization pathways for thermochemical biofuel technologies.[50]

By using the combined feedstock which is a combination of two or more distinct types of biomasses, can reduce risks and costs due to the variety of biomass options available [26]. Biofuel upgrading, especially through catalytic processes, enhances commercial viability which is useful for biofuel technology. Catalysts such as Ni, zeolite, and Al_2O_3 reduce the acidity and oxygen compounds which are present in bio-oil.[39] This catalytic pyrolysis is more economically favourable due to lower equipment needs [27, 31,]. Recycling gases produced during catalytic pyrolysis process is another method to enhance economic potential.

6. Discussion

Bio-oil production costs vary widely which depends upon plant scale, feedstock type and process configuration. Recently reported costs range from as low as USD 1.85 per gallon, particularly for optimized systems utilizing heat integration with feedstocks such as sludge scum and rice husk smaller scale operations. Systems using heat integration catalytic upgrading or co-product valorisation consistently showed improved economic performance. The use of mobile pyrolysis systems and feedstock blending also achieve to reduce production costs and increase biomass supply fluctuations.

These observations highlight the importance of creating policies that support more modular, scalable, and heat-integrated pyrolysis systems, particularly in areas with a wide variety of available raw materials. Further study in research to improve reuse of catalyst, streamline biomass transport and recover heat produced in process could make these systems much more cost effective. To encourage growth in this area government may consider fast pyrolysis technologies in renewable fuel standards.

The global biomass market is continuously experiencing significant growth driven by the actively participation of leading companies within the industrial section. These organizations are making investments into innovative biomass technologies and projects contributing to the increased affordability and accessibility of biomass as a sustainable energy source for the society.

7. Conclusion

Biomass as a feedstock replacement for the renewable energy sources represents an opportunity to produce fuels and chemicals from non-fossil-based feedstocks. Study gives a baseline to assess the quantitative target as a percentage of the total output of the end products. This review focused on four topics: (A) Biomass to bio-oil chemistry, (B)Processes to produce products through upgradation of bio-oil, by two pathways such as catalytic and non-catalytic, (C) Reactors used to process biomass and (D) process economics.[40] By combining all these factors can serve as a guide to assess a targeted product for scale-up. The review is helpful to study the to a roadmap for transitioning to renewable biomass feedstock-based transportation fuels and chemicals. However, the key to this transition is process economics advances in reactor design that, coupled with efficient catalysts. Other approaches under development such as co-processing of biomass with plastic and sludge waste [28] and microwave heating for processing make biomass process attractive [29, 51]. These advances help biomass emerge as competitive domestic feedstock in building a low-carbon energy future for the society.

Author Contributions

All authors contributed equally for this article. All authors read and approved the final manuscript. All authors are aware of the submission and agree to its publication.

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