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Integrated processes of anaerobic digestion and pyrolysis for higher bioenergy recovery from lignocellulosic biomass: A brief review

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ABSTRACT

Climate change, a serious environmental problem arises with global warming, rooting in the overuse of fossil fuel and affecting numerous people all over the world. However, the demands human makes on the natural resources will grow even faster. Lignocellulosic biomass is the largest and most sustainable energy source but has not been utilized well. Therefore, requirements for full utilization of renewable bioenergy sources and practical application of recycle-bioenergy technologies are extremely urgent. Anaerobic digestion and pyrolysis are two promising technologies to degrade lignocellulosic biomass, producing multiple value-added and renewable bioenergy products. The integration of anaerobic digestion and pyrolysis is a new concept appearing in recent years but has drawn much attention from researchers. It is suggested that the integration will open up new interesting pathways for combining biological and thermochemical processes to obtain higher bioenergy recovery from lignocellulosic biomass. This paper briefly reviews recent development and the feasibility of integrated processes. The integration of anaerobic digestion and pyrolysis is designed for giving a full play to advantages of them, achieving significant efficiency gains and maximizing the bioenergy yields extracted from a certain amount of lignocellulosic biomass. Besides, the effects of significant process factors on the yields and properties of bioproducts are introduced. Further optimizations and future challenges for integrated processes are also mentioned.

1. Introduction

The twenties century saw great changes in the conditions of human life, higher living standards along with worse environmental conditions. For decades, the over-use of fossil fuels has brought about many economic and environmental challenges. In developing countries, people in many rural areas live and work mainly relying on traditional energy sources like crop residues, firewood and paraffin because of the lack of new techniques for recycling energy. Traditional methods to obtain energy are not only expensive and inefficient, but time-consuming and not eco-friendly. Considering the limited amount of non-renewable resources, those traditional fossil fuels will be used up in the near future. Consequently, requirements for utilization of renewable energy sources and application of recycling technologies are extremely urgent.

1.1. Lignocellulosic biomass

More and more researchers are studying various renewable energy sources which are sustainable and environmentally friendly. Among these sources, lignocellulosic biomass is recognized as the largest and most sustainable energy source all over the world [1]. There is an annual estimated about 2.2×10^{11} t of dry lignocellulosic biomass, while only 1.2×10^{10} dry tons is available on a sustainable basis [2]. Lignocellulosic biomass is predicted to provide approximately 38% of the world's direct fuel and 17% of the world's electricity by 2050 [3]. In nature, lignocellulosic biomass is an abundant organic source, including agricultural residuals and energy crops. There is considerable amount of lignocellulosic residues accumulating from agricultural, forestry and other mankind activities, which contain large quantities of energy. Generally, lignocellulose is composed of cellulose (35–50%), hemicellulose (20–35%), lignin (10–20%), and other compounds [4]. Among them, lignin is the most recalcitrant component and the second most abundant organic compound in nature. In detail, the dense structures of cellulose–hemicellulose–lignin complexes are linked together, composing the secondary cell walls of terrestrial plants as the major barrier to the conversion of lignocellulosic biomass into biogas [5].

For these years, recycling technologies of lignocellulosic biomass have been applied widely in developed countries as the quantities of

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traditional fossil fuels decline rapidly [6]. Lignocellulosic biomass features large potential and various social and environmental benefits as a regenerative energy source. There will be less greenhouse gases or contaminated gases like CO_2 and SO_2 released during the conversion of lignocellulosic [7]. What's more, liquid biofuels can be produced through various biomass conversion pathways as a promising substitute for petroleum fuel used in transport sector [8].

1.2. Anaerobic digestion

Anaerobic digestion (AD) is a promising technology that recovers bioenergy from lignocellulosic biomass or wastes [9]. This technology converts biodegradable substrates into biogas (a mixture of about 60–65% CH_4 and 35–40% CO_2) through a community of anaerobic microorganisms [10]. Commonly, AD of organic substrate includes four main procedures: hydrolysis, acidogenesis, acetogenesis and methanogenesis, requiring strict anaerobic conditions to proceed, and hydrolysis is generally considered as the rate-limiting step [11,12].

Based on the characteristics of organic substrates (OS), anaerobic digestion can be categorized as wet (10% Total Solids, TS), semi-dry (10–20% TS) and dry (20% TS) bioconversion process [13,14]. Both wet [15] and dry [16] anaerobic processes have incomparable advantages and some shortages in the bioconversion of lignocellulosic biomass.

In recent years, with the deeper understanding of the effects of feedstocks composition on product yield, anaerobic co-digestion has received more and more attention [17,18]. Anaerobic co-digestion uses more than one substrate to optimize the ratio of carbon to nitrogen (C/N ratio), achieving a nutrient-balance and maximizing the yield of products like methane [19,20]. Therefore, anaerobic co-digestion has more benefits than single-substrate anaerobic digestion [21,22].

1.3. Pyrolysis

Pyrolysis is an attractive alternative technology to attain bioenergy because of its carbon negative property [23,24], maximizing the production of biogas, bio-oil and biochar [6,25]. Generally, the process of pyrolysis of biomass can be divided into four stages: moisture evolution, hemicellulose decomposition, cellulose decomposition and lignin decomposition [26]. In absence of oxygen, chemical bonds are broken and new compounds are formed. Then organic matters are converted into three phases: gaseous (or syngas, mainly CO_2, H_2 and CO), liquid (bio-oil) and solid (biochar) fractions, all of which could be used for electricity generation [27,28]. Among them, bio-oil has the potential to be applied as renewable biofuels for transport, power generation, or combined heat and power application [29,30]. When biochar blending was applied with fertilizers in the cropland as a soil amendment, net CO_2 emissions reduction was achieved [31]. Crop yield was enhanced, and water and fertilizer efficiency were increased [32,33].

Pyrolysis processes fall into three main categories, slow (or conventional) pyrolysis, fast pyrolysis and flash pyrolysis, as shown in Table 1 [34,35]. More details in those three types of pyrolysis were discussed in [36–38].

1.4. Bioproducts

Through anaerobic digestion and pyrolysis, bio-oil, biogas and biochar are produced from the conversion of lignocellulosic biomass. Those bioproducts have the potential to substitute traditional fossil fuels, and mitigate the deterioration of environment.

Bio-oil could be considered as a substitute for petroleum because they have something significant in common, such as the calorific energy content [39]. Thus, it can serve in many operations like boiler systems for heat generation or diesel engines for power generation [30,40]. Besides, it can be used for producing different chemicals [7].

As an environmentally friendly bioenergy, biogas could realize the sustainable development, consisting of methane, carbon dioxide and a small quantity of other gases and trace elements. Therefore, biogas can satisfy the energy demand of the rural population as a substitute for firewood [41]. Nowadays, biogas has been applied for combined heat and power generation (CHP) or upgraded and fed into natural gas grids [42].

Biochar has the potential to be applied as natural fertilizer [43] or solid biofuel [44]. By the year 2050, possibly about 80% of all crop and forestry residues will be converted to biochar applied for energy production or soil conditioner [45]. And it is noticeable that biochar could effectively remove heavy metals from aqueous solutions [46]. Besides, previous studies showed that biochar can reduce nutrient leaching in soils [47], increase nutrient availability for plants and improve the efficiency of fertilizers [48]. The current interest on biochar is mainly in its long-term soil carbon sequestration which can mitigate global warming [49].

1.5. Integration of anaerobic digestion and pyrolysis

The integration of various technologies works as a leverage in promoting “circular economy”, aiming at improving both resource use and operation efficiency. Moreover, using an integrated process may overcome defects in each individual process. In this aspect, the integration of anaerobic digestion with pyrolysis can contribute to a new highly effective conversion process. In 2014, the “Supergen” Bioenergy Hub launched a project combining biological (anaerobic digestion) and thermal (pyrolysis) processes to improve the net energy and product yields from further decomposing the residual organic fractions of municipal solid waste [50]. At the same time, more and more researchers are focusing on thoroughly degrading lignocellulosic biomass through this combination to achieve sustainable development.

Generally, lignocellulosic biomass through anaerobic digestion can be bioconverted into biogas (mainly CH_4 and CO_2). After pyrolysis, in the absence of oxygen, biomass can be degraded into syngas (mainly H_2 and CO_2), bio-oil and biochar. Through the combination, resource use efficiency can be significantly improved. On the one hand, after anaerobic digestion, more energy in the raw feedstocks was transferred into pyrolysis volatiles and biogas [51]. Biochar produced from pyrolysing anaerobic digestate had lower lower heating value (LHV) than biochar from pyrolysing raw feedstocks. Besides, this type of biochar can fix heavy metals and nutrient elements like P, K and Ca in digestate, preventing them from releasing into aqueous phase [52]. On the other hand, during the AD process, some recalcitrant components of lignocellulose biomass like lignin would prevent anaerobic micro-

Table 1
Pyrolysis technologies, corresponding process conditions and product distribution [34,35].

Pyrolysis technologies	Process conditions			Products		
	Temperature	Heating rate	Retention time	Char	Bio-oil	Syngas
Slow Pyrolysis	400–600 °C	5–7 °C/min	5–30 min	< 35%	< 30%	< 40%
Fast Pyrolysis	400–600 °C	300 °C/min	< 5 s	< 25%	< 75%	< 20%
Flash Pyrolysis	400–950 °C	1000 °C/s	30 ms~1.5 s	< 25%	< 70%	< 16%