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Fuzzy logic-based predictive model for biomass pyrolysis

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HIGHLIGHTS

- Proposing new approach to tackle the problem of biomass pyrolysis modeling considered uncertainty happened in the system.
- Model giving good predictions of two biomass pyrolysis conversions without relying on experimental data.
- Potential model to develop to predict other reactions.

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ABSTRACT

As pyrolysis reaction is one of an important reaction applied to lignocellulosic biomass in order to transform it to be user-friendly energy form recognized as prospective alternative energy source, the reaction has been widely investigated in order to understand the mechanisms and kinetics of the pyrolysis. However, modeling pyrolysis of biomass is full of complication. As lignocellulosic biomass is not a homogeneous chemical source, chemical compositions in biomass are also uncertain and they vary even in the same biomass. The reactions of imprecise chemical compositions in biomass affects the capability of deterministic model in modeling chemical reaction since available deterministic models are designed to model homogeneous and precise chemical compositions. With this problem, it raises the idea of using model which has ability to calculate something ambiguous. Since the fuzzy logic-based model which is adaptive network-based fuzzy inference system (ANFIS) is built to calculate uncertainty, the model should be suitable to handle uncertainty which is imprecise chemical compositions in the reaction. The proposed model is built with four input variables: the reaction time, amount of cellulose component, amount of hemicellulose component, and amount of lignin component in biomass. The model is trained with tuning datasets which are the pyrolysis datasets of lignin, cellulose and *Madhuca* before applying to predict the pyrolysis reactions of *Pongamia pinnata* and *Jatropha curcas*. The comparative results show that the proposed model can correctly predict 91.82% and 97.29%, respectively, of the pyrolysis reactions of *P. pinnata* and *J. curcas*. As the ANFIS model gives good prediction in modeling pyrolysis of two different biomasses, the model can be applied to predict the pyrolysis reaction of other lignocellulosic biomass products.

1. Introduction

At present, fossil fuels are the dominant source of energy for myriad of economic activities, including electricity generation, transportation, industry and so on [1]. The use of fossil fuels at the same time produces and releases greenhouse gases (GHGs) into the atmosphere and contributes to the environmental degradation. According to [2], several GHGs which cause climate change and global warming are produced and emitted during the burning of fossil fuels.

Along with the growth in the global population and the subsequent economic expansion comes a surge in the energy demand, thereby exacerbating the fast-depleting fossil fuel reserves. This in turn necessitates a continuous search for new energy sources [3]. Nevertheless, due to the pollution-laden nature of fossil fuels, the new energy sources need to be environmentally-friendly and renewable, in addition to in ample supply to meet the human energy requirements. Biomass is thus a promising energy source due to the abundance of biomass resources, in particular agricultural wastes such as rice straw, rice hulks. A common practice to the management of agricultural wastes is open-air burning which causes air pollution and is harmful to the environment [4,5]. Thus, an attempt to convert the agricultural wastes into an energy product is beneficial to both agriculturists and the environment.

Among the existing biomass conversion techniques, the thermochemical conversion processes, i.e. pyrolysis, gasification and combustion, are the most promising techniques since they are

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readily scaled up to industry size. Specifically, pyrolysis is a thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen. Three major outputs of biomass pyrolysis are charcoal, bio-oil and volatiles. Meanwhile, an efficient pyrolysis process requires knowledge of key pyrolysis parameters and their effects on the process.

Currently, a number of kinetic models of biomass have been proposed, including the global kinetic model, three-parallel-reactions model, competitive models, models with secondary tar cracking, Shafizadeh and Bradbury model, distributed activation energy model and so forth. Huang et al. [6] utilized the global kinetic model to evaluate the pyrolysis reaction of filter paper, xylan and alkali lignin as the representatives of cellulose, hemicellulose and lignin, respectively. Sharma and Rao [7] studied the pyrolysis of rice husks in both grain and powder form in nitrogen; and documented that the kinetic parameters from the isothermal experiments were consistent with the non-isothermal values. Buessing and Goldfarb [8] investigated the kinetics of pyrolysis of three different particle-size fractions of cabbage palm leaf, stalk and trunk using the nonisothermal thermogravimetric analysis under a constant nitrogen flow, in which the Arrhenius equation was utilized to calculate the activation energy and pre-exponential factor. Barneto et al. [9] employed the three-parallel-reactions model to model the pyrolysis reaction of rice straw, empty fruit bunches and *Hesperaloe*. González et al. [10] modeled the pyrolysis of cherry stones using a three-independent-parallel first-order reaction model, and Di Blasi and Branca [11] used the competitive models to study the pyrolysis reaction of beech wood powder. In addition, Rath and Staudinger [12] deployed the tar cracking model to examine the pyrolysis reaction of spruce wood. Dauenhauer et al. [13] utilized the Shafizadeh and Bradbury model to simulate the pyrolysis of cellulose. Ounas et al. [14] used the distributed activation energy model to describe the pyrolysis reaction of olive residues and sugar cane bagasse, and Ma et al. [15] deployed such a model to determine the pyrolytic characteristics and kinetics of corn stove. Gašparoviè et al. [16] proposed a distribution activation energy model (DAEM) to describe the pyrolysis decomposition of wood. The model is able to describe the integral decomposition curve for wood but fails to describe the differential curve. Generally speaking, DAEM does not accurately describe biomass pyrolysis.

In addition, Lanzetta and Di Blasi [17] proposed a two-stage model to study the degradation kinetics of wheat straw and corn stalks under isothermal conditions; and reported that volatiles from both biomass sources released in the first stage were 10 times faster than in the second stage. Biney et al. [18] investigated the pyrolysis kinetics of arundo, sawdust, corn stove and switch grass biomass using the multi-stage kinetic model. Sharma et al. [19] utilized the finite forward difference method to study the thermal degradation kinetics of *Jatropha curcas* de-oiled cake. Anca-Couce and Obernberger [20] modeled the pyrolysis of hard and soft wood by using secondary charring reactions. Mahmoudi et al. [21] utilized semi-resolved model to calculate pyrolysis of wet wood. Kirtania and Bhattacharya [22] modeled two types of biomass (spruce sawdust and coconut shell) by using distributed activation energy model (DAEM) incorporated in a particle model. Bañón et al. [23] utilized three independent nth order reactions to model pyrolysis of chrome tanned leather treated with NaOH. Notwithstanding, all the aforementioned models are deterministic approaches in which the reaction results have previously been experimentally proven, and the aims of those studies are merely to describe in greater detail the evolutions inside the reactor. On the contrary, the approach adopted for this research paper is of uncertain (fuzzy) nature.

Modeling the biomass pyrolysis is complicated by many factors. Especially, a complex mixture of several organic and inorganic compounds in biomass and high reaction temperature cause hundreds of reactions take place during pyrolysis reactions. Therefore, in order to simplify model, some researchers chose to model on specific biomass such as work from Ronda et al. [24], Alias et al. [25], Mabrouki et al. [26], and Sun et al. [27]. In addition, some researchers tried to simplify biomass chemical composition. For example, Liu et al. [28] chose to model pyrolysis of $C_{19.82}H_{24.52}O_{11.86}$ as representative of biomass.

As lignocellulosic biomass is not a homogeneous chemical source, chemical compositions in biomass are also uncertain and they vary even in the same biomass. Serapiglia et al. [29] investigated how variations in biomass compositions influence the pyrolysis conversion efficiency and pyrolysis oil yields of novel genotypes of shrub willow. The authors documented that the pyrolysis oil yields were positively correlated to the cellulose content and proposed that better biomass sources would lead to improvement in bio-oil quality and increase bio-oil yield. They concluded that the improvements in biomass breed can lead to improvements in bio-oil yield and quality. Moreover, the finding suggested that there were variations in biomass chemical compositions even in the same species plant. This uncertain chemical composition resulted in complexity of reaction modeling as it was challenged to identify all the chemical compounds and also quantify the composition of the known chemical compounds.

The reactions of imprecise chemical compositions in biomass affects the capability of deterministic model in modeling chemical reaction since available deterministic models are designed to model homogeneous and precise chemical compositions. With this problem, it raises the idea of using model which has ability to calculate something ambiguous. This research has used the adaptive network-based fuzzy inference system (ANFIS) to model biomass pyrolysis. Since ANFIS is built to calculate uncertainty, the model should be suitable to handle uncertainty in biomass pyrolysis. The aim of this research is to establish a generic model that could be applied to predict the pyrolysis of non-specific lignocellulosic biomass. In order to verify that the model reach the aim of this research, the proposed ANFIS model is utilized to predict the total pyrolysis reactions of *Pongamia pinnata* and *J. curcas* in nitrogen atmosphere.

P. pinnata is an indigenous plant of Bangladesh, India, Myanmar, Nepal and Thailand and is widely used as biomass material. The plant can grow on most soil types, ranging from stony to sandy to clayey and is also highly tolerant of salinity. *P. pinnata* is a fast-growing tree which can reach 40 feet in height and spread, forming a broad and spreading canopy casting moderate shade [30]. *P. pinnata* oil is a preferable source of biodiesel due to several comparable characteristics to the petroleum-based diesel, e.g. the flash point, cetane value, specific gravity and viscosity. By comparison, the cetane value in *P. pinnata* oil (51) is slightly higher than that of diesel (47.8), while the sulfur in *P. pinnata* oil (0.13) is lower than that in diesel (0.16) [31].

There are research studies on the pyrolysis of *P. pinnata* utilizing variety models. However, these models are only applicable to *P. pinnata*. Prasad et al. [32] studied the pyrolysis of *P. pinnata* residue (de-oiled cake) and found that most of the material (60%) decomposed in stage-II between 166 °C and 480 °C. The kinetic parameters obtained by the differential and Flynn–Wall–Ozawa (FWO) methods indicated their respective activation energies in the range of 68.8–177.9 kJ/mol and 41.3–161.8 kJ/mol. Islam et al. [33] investigated the pyrolysis reaction of *P. pinnata* under nitrogen environment with varying heating rates of 5 °C/min, 10 °C/min and 20 °C/min; and determined the kinetic data using the Kissinger–Akahira–Sunose and FWO methods. The activation energy values obtained with the two methods were respectively 61.06 and 68.53 kJ/mol. Chutia et al. [34] investigated the pyrolysis of *P. pinnata* in a fixed-bed pyrolyzer at temperatures ranging from 350 to 600 °C

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