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Prediction of biochar yield from cattle manure pyrolysis via least squares support vector machine intelligent approach

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HIGHLIGHTS

- Intelligent approach is applied for predicting cattle manure biochar yield.
- Two intelligent models, ANN model and LS-SVM model, are developed.
- LS-SVM model has a better predicting accuracy and robustness than ANN model.

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ABSTRACT

To predict conveniently the biochar yield from cattle manure pyrolysis, intelligent modeling approach was introduced in this research. A traditional artificial neural networks (ANN) model and a novel least squares support vector machine (LS-SVM) model were developed. For the identification and prediction evaluation of the models, a data set with 33 experimental data was used, which were obtained using a laboratory-scale fixed bed reaction system. The results demonstrated that the intelligent modeling approach is greatly convenient and effective for the prediction of the biochar yield. In particular, the novel LS-SVM model has a more satisfying predicting performance and its robustness is better than the traditional ANN model. The introduction and application of the LS-SVM modeling method gives a successful example, which is a good reference for the modeling study of cattle manure pyrolysis process, even other similar processes.

1. Introduction

With the increasing cattle feeding operations, more and more cattle manure is produced and the disposal problem cannot be neglected (Saunders et al., 2012; Venglovsky et al., 2009). Since cattle manure is high in organic materials and contains nutrients essential for crop production, it is popular to use cattle manure as fertilizer (Kapkiyai et al., 1999). However, the use of cattle manure in an unmodified form for soil improvement can cause some environmental and food safety problems. Untreated cattle manure is a significant source of ammonia volatilization which can lead to an adverse effect on crop growth (Chadwick, 2005). In addition, cattle manure can also be an important source of potentially dangerous pathogens and nitrates that may be transported to the surface and ground water (Uzoma et al., 2011). Composting is a widely used disposal technology, which can produces a stabilized product that can be stored or spread on land with little or no odor, pathogens, nitrates, and weed seeds (Hao et al., 2001). However, C and N losses during composting not only reduce the agronomic value of compost as fertilizer, but also contribute to emissions of greenhouse gas, e.g. CH_4, CO_2, and N_2O (Brown et al., 2000; Hao et al., 2001). Another popular technology used for the reduction of cattle manure is anaerobic digestion. Unfortunately, anaerobic digestion causes similar environmental pollution as composting process (Macias-Corral et al., 2008; Sweeten et al., 2003). More importantly, they are both a slow process that results in the release of emissions over a longer period of time (10–40 days) (Macias-Corral et al., 2008).

Compared to the above biochemical method, thermochemical conversion represents a promising alternative due to the advantages of high temperature elimination of pathogens, drastic reduction of waste stream volume, and production of green energy or other value-added products (Wu et al., 2013; Zhang et al., 2009). Thermochemical conversion can be subdivided further into combustion, gasification, and pyrolysis. Pyrolysis is not only as a single process, but also as the first step to combustion and gasification. In general, with a low reaction temperature, a slow heating rate, and a long holding time, the pyrolysis produces mainly biochar (Xu and Chen, 2013). The obtained biochar contains higher levels of essen-

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tial plant nutrients and higher cation exchange capacity than plant based biochars due to the high nutritive value of cattle manures, and has emerged as a viable option for sequestering carbon in soil (Uzoma et al., 2011). Cao and Harris (2010) have conducted the dairy-manure-derived biochar by considering physical, chemical, and mineralogical properties specifically related to its potential use in remediation. Experimental results indicated that dairy manure can be converted into biochar as an effective adsorbent for application in environmental remediation. The cattle manure biochar is also a good precursor in the production of activated carbons (Qian et al., 2007). Moreover, in the term of energy utilization, it can be used to produce gas products by further gasification in a multi-stage thermochemical process, where high gas purity with low levels of tar and high process efficiencies with high char conversion rates are possible (Heidenreich and Foscolo, 2015). In this context, it is necessary to clarify the biochar properties under different operating conditions, e.g. biochar yield, pH, electro conductivity, surface area, elemental composition, energy content, etc (Cantrell et al., 2012; Xu and Chen, 2013).

As far as we know, it is quite expensive and time consuming to obtain these properties by experimental tests, especially to conduct large-scale experiments. It is an interesting idea that the biochar properties within the considered operating ranges can be estimated only based on the lowest possible number of experimental data. Intelligent modeling is a kind of data mining method, which can predict effectively system outputs by learning and mining system characteristics from limited experimental data (Fayyad et al., 1996; Pandey et al., 2015). For instance, in the recent past artificial neural networks (ANN), a sort of extensively used intelligent modeling approach in the fields of pattern recognition, signal processing, function approximation, and process simulations, has received increasing attention as a tool in renewable energy system prediction and modeling (Mikulandrić et al., 2014). Guo et al. (2001) developed a hybrid neural network model to predict the product yield and gas composition of biomass gasification in an atmospheric pressure steam fluidized bed gasifier. The results revealed that the ANN model prediction was better than the traditional regression models. Dong et al. (2003) adopted ANN model to predict the lower heating value of municipal solid waste, and it was also demonstrated that the ANN model has better precision over the traditional model. Recently, Puig-Arnavat et al. (2013) and Mikulandrić et al. (2014) have successfully used the ANN modeling approach for biomass gasification processes in fluidized bed gasifiers and fixed bed gasifiers, respectively; the ANN models showed good capability to predict biomass gasification process parameters.

In addition to ANN intelligent modeling approach, the support vector machine (SVM) is another new powerful tool, proposed by Vapnik (2000) for intelligent modeling. The SVM intelligent approach is based on the structured risk minimization principle that seeks to minimize an upper bound of the generalization error instead of the empirical error as in ANN method (Vapnik, 2000; Wu et al., 2008). A particular advantage of SVM over ANN is that it can be analyzed theoretically by means of concepts from statistical machine learning theory, and at the same time tends to find a global solution during the training since the model complexity has been taken into consideration as a structural risk in SVM training (Ren, 2012; Wu et al., 2008). The ANN uses the gradient descent learning algorithm, and intends to converge to local minima. As a result, it often suffers from the over-fitting problem, especially for a complicated nonlinear process (Kankar et al., 2011; Ren, 2012).

As mentioned above, biochar application is greatly wide, including as soil amendment, environmental remediation, precursor of activated carbons, gasification raw to produce hydrogen-rich gas, etc. For these applications, biochar yield derived from pyrolysis is a common and key parameter. Therefore, in this research, we take the estimation of biochar yield during cattle manure pyrolysis as an example to conduct the application of SVM intelligent approach. In addition, considering the computational difficulty of SVM model requiring the solution of quadratic programming (QP), herein we employ a modified version of SVM called least squares support vector machine (LS-SVM). The LS-SVM is to solve a set of linear equations that is easier to solve than QP problems, while most of the important advantages of SVM are retained (Ahmadi et al., 2015). The results showed that the LS-SVM model has a satisfying predicting performance for the produced biochar during the cattle manure pyrolysis and its predicting accuracy and robustness is better over the traditional ANN model. To the best of the authors' knowledge, this is the first study using SVM intelligent approach to model the pyrolysis characteristics of cattle manures. The SVM modeling, a data-driven modeling process, can easily establish a mathematic model for accurately predicting the cattle manure pyrolysis behavior, which provides a useful reference for the modeling study of the thermochemical disposal process of cattle manures, as well as other similar processes.

2. Methods

2.1. Sample preparation

The cattle manure used was collected from the dongzheng feedlot located in Jiangxia District, Wuhan City, Hubei Province, PR China. The moisture content of fresh cattle manure is 85.12 ± 0.5 wt%. After being dried in a greenhouse, the moisture content of cattle manure samples was reduced to 10.14 wt%. And then, the cattle manure samples in air-dried basis were crushed and screened to 40 mesh (0.63 mm) size particles, and were stored in a closed container to be used for pyrolysis experiments. In addition, the contents of volatile matter, fixed carbon, and ash of the samples in dry basis are 69.51 wt%, 15.12 wt%, and 15.37 wt%, respectively. The ultimate analysis showed that the cattle manure contains 41.13 wt% of carbon (C), 5.89 wt% of hydrogen (H), 2.69 wt% of nitrogen (N), 0.37 wt% of sulfur (S), and 49.92 wt% of oxygen (O).

2.2. Experimental data

The pyrolysis experiments of the samples were performed with a laboratory-scale fixed bed reaction system (SLG1200-100, SHENGLI Test Instruments Co. Ltd, Shanghai, China). Before beginning the heating program for each experiment, the reactor was purged with nitrogen (99.99%) for 30 min to ensure an inert atmosphere for pyrolysis reaction. At the end of pyrolysis experiment, the nitrogen was introduced once again to cool the produced biochar. In this research, five operating parameters, e.g. pyrolysis temperature (°C), heating rate (°C min^{-1}), holding time (min), moisture content (%), and sample mass (g), were considered to prepare experimental data for the modeling and testing of the developed models. Since the aim of cattle manure pyrolysis is to produce biochar, the pyrolysis temperature is set within a low temperature range, e.g. from 400 to 600 °C, at the same time with a slow heating rate and a long holding time. The heating rate and holding time are taken into account from 4 to 16 °C min^{-1} and from 40 to 100 min, respectively. The moisture content and sample mass are set from 45% to 85% and from 5 to 20 g, respectively. Herein, the sample mass is in air-dried basis, and the corresponding moisture content is achieved by adding distilled water. In this way, a data set with 33 experimental data was prepared, as shown in Table 1.

2.3. LS-SVM principles

LS-SVM intelligent approach considers the problem of approximating a given dataset $\{(x_1, y_1), (x_2, y_2), \ldots, (x_N, y_N)\}$ with the follow-