Bioresource Technology 275 (2019) 338–344

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

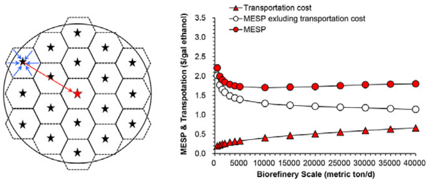
Case Study

Constructing super large scale cellulosic ethanol plant by decentralizing dry acid pretreatment technology into biomass collection depots

Gang Liu, Jie Bao*

State Key Laboratory of Bioreactor Engineering, East China University of Science and Technology, 130 Meilong Road, Shanghai 200237, China

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Decentralized pretreatment operation
Dry acid pretreatment
Cellulosic ethanol
Biorefinery scale
Biomass supply

ABSTRACT

Commercial cellulosic ethanol plants require mature and year-round biomass feedstock supply. Decentralizing pretreatment operation from central ethanol plant into local regional biomass collection depots provides an important solution to reach this goal. In this study, we introduced a newly established pretreatment technology, dry acid pretreatment, into the decentralized pretreatment operation by its advantages on zero wastewater generation and high volumetric density. Collection radius of crop residues feedstock is extended to nearly 100 km by decentralizing dry acid pretreatment, and biorefinery scale for cellulosic ethanol production is increased to the scale of modern petroleum refining factories in the densified agricultural regions in China and USA with the minimum ethanol selling price of below $2/gal. The technology overcomes the barrier of cellulosic ethanol cost increase with increasing biomass collection range, and provides a methodology for optimal supply method of large biorefinery plants in agricultural countries.

1. Introduction

Several commercial biorefinery plants for production of cellulosic ethanol had been put into operation in recent few years (Lynd et al., 2017). The scale of these plants is less than half million metric tons of feedstock processing capacity annually, far below the of integrated petroleum refinery plants (tens or even hundreds million metric tons of petroleum processing annually). In view of economics of scale, the increase of production scale from 25 to 125 million gal of ethanol per year will lead to a cost reduction of $0.2–0.3/gal (Kocoloski et al., 2011). The high processing capacity of crop residues biomass certainly delivers a huge challenge on logistic system including field collection, baling, storage, and transportation in a short harvest period (Tembo et al., 2003; Kumar and Sokhansanj, 2007).

Crop residues biomass feedstock accounts for 35%–50% of the overall production cost of cellulosic ethanol, in which the cost of transportation and storage accounts for 50%–75% (Hess et al., 2007). The inherent properties of crop residues biomass such as low density, geographical dispersibility, prone decomposition and fire risk significantly increase the transportation and storage cost (Kim and Dale,

---

Abbreviations: RBPD, regional biomass processing depot; MESP, minimum ethanol selling price; AFEX, ammonia fiber expansion pretreatment; DryPB, dry acid pretreatment and biodetoxification biorefining technology; NREL, national renewable energy laboratory; SSCF, simultaneous saccharification and co-fermentation; SHCF, separate hydrolysis and co-fermentation

* Corresponding author.

E-mail address: jbao@ecust.edu.cn (J. Bao).

https://doi.org/10.1016/j.biortech.2018.12.061
Received 12 November 2018; Received in revised form 17 December 2018; Accepted 18 December 2018

Nomenclatures

P	production of crop grain, metric ton
δ	residue to product ratio of crops
S_r	area of administrative region, km^2
ε	percentage of available biomass for biorefinery use in the theoretical output of crop residues, %
α	the collectable quantity of crop residues per unit area, metric ton/km^2
C_p	purchasing cost of crop residues, \$
C_{pc}	unit price of per metric ton crop residues, \$/metric ton
C_t	transportation cost of crop residues, \$
C_o	other costs, \$
Q_t	total theoretical quantity of crop residues, metric ton
Q	total quantity of crop residues available for biorefinery use, metric ton
R	total collection radius, km
C_{t1}	total transportation cost, \$
r	straight transport distance of crop residues, km
β	road tortuosity factor
P_{m1}	transport cost per unit distance of unit mass bulk crop residues, \$/(metric ton·km)
P_v	transport cost per unit distance of unit volume cargo, \$/(m^3·km)
ρ_1	bulk density of crop residues, metric ton/m^2
w_1	moisture content of crop residues, %
θ	loss factor of transportation and storage, %
S_i	area of ith biomass collection depots, km^2
P_{m2}	transport cost per unit distance of unit mass pretreated crop residues, \$/(metric ton·km)
ρ_2	tapped density of pretreated crop residues, metric ton/m^3
w_2	moisture content of tapped crop residues, %
Q_i	available quantity of crop residues for ith collection depots, metric ton
L_i	actual transport distance of crop residues from ith collection depots to biorefinery, km
C_{t2}	total transportation cost for decentralized biomass supply method, \$
R_i	collection radius of ith collection depots, km
Q_c	available quantity of crop residues for central zone where biorefinery plant is located in, metric ton
R_c	collection radius of central zone where biorefinery plant is located in, km
ρ	density of transport material, metric ton/m^3
w	moisture content of transport material, %

2015a,b; Dale, 2017). Amount of work were done to optimize the supply chain of biorefinery, such as choosing road, railway or waterway transportation based on the biomass form, optimizing the stover harvest strategy, and developing the integrated biomass supply chain optimization model (Karlen et al., 2011; Lin et al., 2014; Lu et al., 2015). In the conventional biomass collection system, crop residues is harvested from farmland into various biomass collection depots, then densifying into bales or pellets or briquettes before transporting into central biorefinery plant (Sokhansanj et al., 2010; Eranki et al., 2011; Hoover et al., 2014; Martelli and Bentini, 2015). In recent few years, Dale and his colleagues in Michigan State University proposed a concept of "regional biomass processing depot (RBPD)", in which the pretreatment operation of biorefinery processing is moved from central biorefinery plants into biomass collection depots (Eranki et al., 2011; Bals and Dale, 2012; Kim and Dale, 2015a,b). By conducting this decentralized pretreatment operation at depots, the transportation cost of the densified crop residues biomass is significantly reduced. However, the prerequisite requirement of the decentralized pretreatment operation should be a "dry" process without wastewater discharge, because dry solid biomass form is required for transportation and the depots in rural area are generally lack of wastewater treatment facilities (Eranki et al., 2011). Ammonia fiber explosion (AFEX) pretreatment is the firstly applied into the decentralized pretreatment operation for its merit of zero wastewater discharge and dry biomass morphology after pretreatment (Bals and Dale, 2012; Lamers et al., 2015). But high energy input is required for ammonia recycling and biomass densification (milling, drying and pelletizing) (Hoover et al., 2014; Bals et al., 2014; Lamers et al., 2015). Steam explosion is another potential option for its low wastewater generation and relatively dry biomass morphology, but it also requires high energy input and expensive pressure vessels for explosion operation (Zhang et al., 2016a). Others pretreatment methods such as conventional dilute acid pretreatment (Saha et al., 2005; Lloyd and Wyman, 2005), dilute alkaline (or deacetylation and mechanic refining) (Kim et al., 2016; Chen et al., 2016), neutral hot water (Ko et al., 2015; Huang et al., 2016), ionic liquid (Mora-Pale et al., 2011; Konda et al., 2014) are not suitable for decentralizing pretreatment operation because of vast wastewater generation.

In our previous studies, a modified dilute acid pretreatment, namely dry acid pretreatment, was developed by significantly increasing the initial biomass solids content to 70% and reducing wastewater generation to zero (Zhang et al., 2011; He et al., 2014a,b). The property well fits the application to the decentralized pretreatment operation at biomass collection depots: the low pH with inhibitor existence created the suitable environment for long term storage; the high accumulative density is suitable for cost effective transportation (Zhang et al., 2016b); the low steam input, low equipment cost and negligible corrosion to pretreatment reactor are suitable for miniaturization at biomass collection depots (Zhang et al., 2010; He et al., 2016; Shao et al., 2017). In this study, decentralized dry acid pretreatment operation at biomass collection depots was evaluated on increasing the capacity of biomass collection to tens of million metric tons of biomass feedstock annually under the minimum processing cost. The distribution of crop residues available for biorefinery use in China and USA were calculated and the potential of biorefinery industrialization in China and USA were evaluated for constructing super large scale cellulosic ethanol plants.

2. Material and methods

2.1. Biomass distribution density estimation available for biorefining use

Biomass feedstock used in this study was agricultural crop residues including corn stover, wheat straw and rice straw. Distribution density of available biomass feedstock for biorefining use is defined as the metric ton of the collectable crop straw per square kilometer (α, metric ton/km^2) and calculated by Eq. (1) (Qiu et al., 2014):

$$\alpha = \frac{P\delta\varepsilon}{S_r} \tag{1}$$

where P is the production of crop grain (corn, wheat, rice) in the designated regions in 2013 (metric ton), δ is the weight ratio of crop residues to grain, ε is the percentage of available biomass for biorefinery use in the theoretical output of crop residues (%), S_r is the area of the designated region (km^2).

2.2. Cost and processing methods of crop residues feedstock

The total cost of crop residues feedstock includes purchase cost (C_p, \$), transportation cost (C_t, \$), and others (loading, unloading, labor and storage) cost (C_o, \$).

The purchase cost C_p is calculated by $C_p = C_{pc} \cdot Q$, where C_{pc} is the unit price of per metric ton crop residues (\$/metric ton), Q is the total quantity of available crop residues (metric ton).

The transportation cost C_t of crop residues depends largely on the volume rather than weight (Gonzales et al., 2013). The assumptions for transportation cost calculation include: (1) collection area is circular and biorefinery plant is located at the center of the circle; (2) farmlands are uniformly distributed and the crop residues biomass production per unit area in the designated regions is same; and (3) no competitors for crop residues feedstock in the collection area, for example biomass power plant.

Two crop residues biomass supply methods are illustrated in this study (Fig. 1). The first option is the traditional centralized supply (Fig. 1a), in which the crop residues is collected from a circular area with the biorefinery plant in the center. The total transportation cost C_{t1} (\$) is calculated based on the method of definite integral element (Aden et al., 2002):

$$C_{t1} = \int_0^R 2\pi r(1-\theta)\alpha\beta r P_{m1} dr = \frac{2}{3}\pi R^3(1-\theta)\alpha\beta P_{m1} = \frac{2}{3}Q(1-\theta)\beta P_{m1}R \tag{2}$$

where $P_{m1} = P_v/[\rho_1(1-w_1)]$, is the transport cost per unit distance of unit mass of the bulk crop residues (\$/(metric ton·km)); P_v is the transport cost per unit distance of unit volume cargo (\$/(m^3·km)); ρ_1 is the bulk density of crop residues (metric ton/m^3); w_1 is the moisture content of crop residues (%); θ is the loss factor during transportation and storage (%); r is the theoretical straight transport distance of crop residues (km); β is the road tortuosity factor for adjustment of the actual transportation distances from straight lines; R is total collection radius (km).

The second option is the decentralized biomass supply method (Fig. 1b), in which the pretreatment operation is decentralized from central biorefinery plants into the biomass collection depots for preprocessing, pretreatment, storage, then transportation to central plants (Fig. 1b). Each collection area is simplified to a circular area (Kim and Dale, 2015a). The total transportation cost C_{t2} (\$) is calculated in Eq. (3):

$$C_{t2} = \sum_{i=1}^{n}\left[\frac{2}{3}Q_i(1-\theta)\beta P_{m1}R_i + Q_i\beta L_i P_{m2}\right] + \frac{2}{3}Q_c(1-\theta)\beta P_{m1}R_c \tag{3}$$

where $R_i = \sqrt{S_i/\pi}$, is collection radius of ith collection depots (km); S_i is the area of ith biomass collection depots (km^2); $Q_i\beta L_i P_{m2}$, is the transportation cost of pretreated crop residues from ith collection depot to the central biorefinery plant (\$); $P_{m2} = P_v/[\rho_2(1-w_2)]$, is transport cost per unit distance of unit mass tapped pretreated crop residues (\$/(metric ton·km)); ρ_2 is tapped density of pretreated crop residues (metric ton/m^3); w_2 is moisture content of tapped crop residues (%); Q_i is available quantity of crop residues in ith collection area (metric ton); L_i is theoretical straight transport distance of crop residues from ith collection depot to biorefinery plant (km); Q_c is available quantity of crop residues in central zone where biorefinery plant is located in (metric ton); R_c is collection radius of central area where biorefinery plant is located in (km).

Other costs (C_o) are calculated by $C_o = 1.61Q(1-w)/\rho$ (Xing et al., 2008), where ρ is density of transport material (metric ton/m^3); w is moisture content of transport material (%).

2.3. Dry acid pretreatment and biodetoxification (DryPB) process

Dry acid pretreatment and biodetoxification (DryPB) process is applied for conversion of lignocellulose feedstock to ethanol (Liu and Bao, 2018) (Fig. 2a). At first, the raw lignocellulose feedstock is de-ashed and grinded after harvest and naturally drying. The pre-processed feedstock and dilute sulfuric acid (5%, w/w) are added into the pretreatment reactor with mass ratio of 2:1 for dry acid pretreatment without wastewater stream generation. Solid state (around 50% solid content) and acid (pH 2.0) pretreated biomass is neutralized to pH 5–6, and then solid state biodetoxified for 36 h. The inhibitor free pretreated biomass is bio-converted to ethanol by simultaneous saccharification and co-fermentation (SSCF) by shortly adapted *Saccharomyces cerevisiae* XH7 with the enzyme (Novozymes Cellic CTec 2.0) dosage of 10 mg proteins per gram of cellulose at 30% (w/w) solids loading. Finally, the fermentation broth is distillated to ethanol stream, and the stillage is filtrated to yield the wastewater stream and the lignin residue cake.

2.4. Process model and techno-economic analysis

Biorefining process chain in decentralized pretreatment operation method is divided into two parts, the first part is in biomass collection depots, where biomass feedstock is pre-processed (dust removing, grinding), pretreated, stored or transported to central biorefinery plant. The second part is in central biorefinery plant, where pretreated

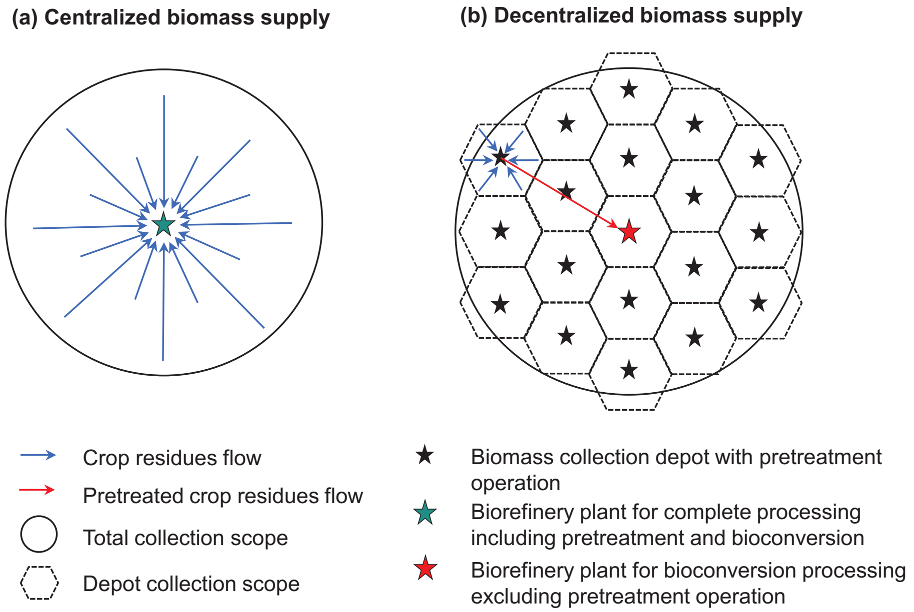


Fig. 1. Schematic diagrams of biomass supply method. (a) Centralized biomass supply; (b) decentralized biomass supply.

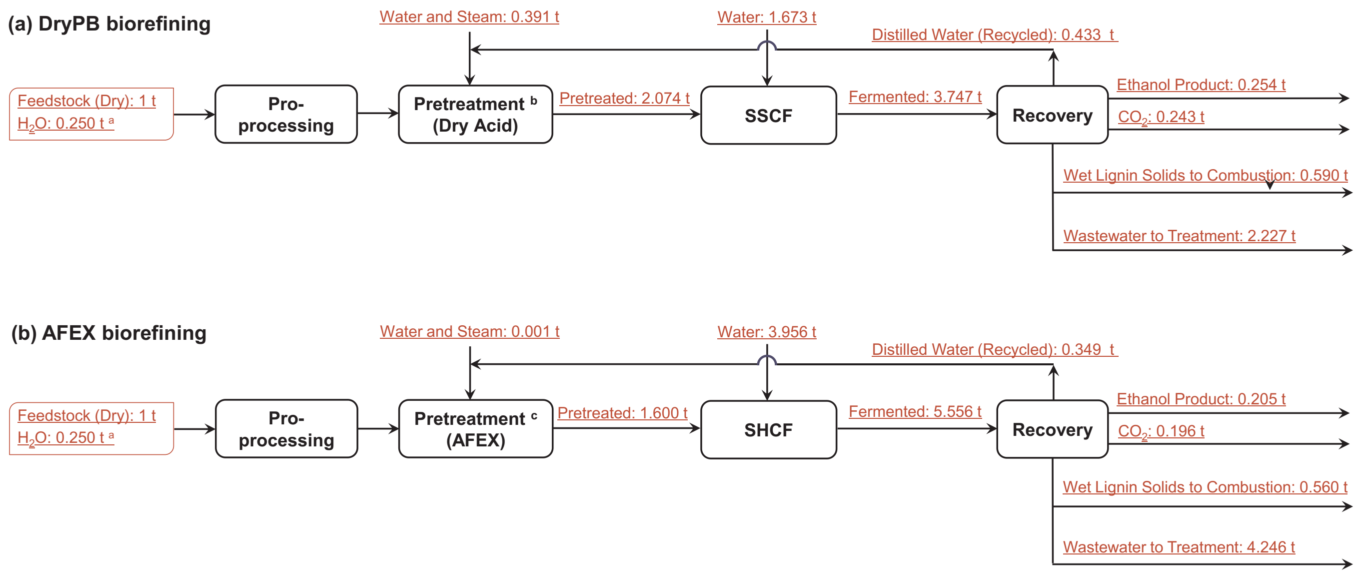


Fig. 2. Flowchart and mass balance of DryPB and AFEX biorefining for cellulosic ethanol production. [a]The general moisture content of raw biomass feedstock is 20%, as 0.250 ton water per ton feedstock; [b]Besides dry acid pretreatment, the biodetoxification operation is need before hydrolysis and fermentation; [c]Additional operations are need to applying for RBPD concept, including milling, drying and pelletizing.

biomass feedstock is biodetoxified, hydrolyzed, fermented, and recovered as fuel ethanol, as well as wastewater treatment, lignin residue combustion, storage, and utilities. The process model was developed on Aspen Plus software (AspenTech Co., Cambridge, MA, USA) and the basic model was cited from the design report of National Renewable Energy Laboratory (NREL) (Humbird et al., 2011) with the changes in pretreatment from conventional dilute acid pretreatment to dry acid pretreatment, in detoxification from ammonia overliming to biodetoxification, in saccharification and fermentation from 20% (w/w) solids loading SHCF (separate hydrolysis and co-fermentation) to higher 30% (w/w) solids loading SSCF (Simultaneous saccharification and co-fermentation) (Liu and Bao, 2017a,b).

The material and energy balance data from Aspen plus modeling were used to design the equipment and determine the chemical usage. The year of 2013 was used as the reference year. The exchange rate from US dollar ($) to Chinese Yuan (CNY) is 1:6.2. The general purpose equipment of pumps, conveyors and rectification columns were quoted from the NREL report (Humbird et al., 2011). The specific equipment of the pretreatment reactors, fermenters and helical agitators, chemicals, and staff wages were modified according to actual situation in China (Liu and Bao, 2017a). Discounted cash flow analysis to determine the minimum ethanol selling price (MESP, $/gal) requires a net present value of zero for 10% internal rate of return after taxes. The techno-economic analysis reported here uses what are known as “n^{th}-plant” economics.

3. Results and discussion

3.1. Decentralizing dry acid pretreatment into biomass collection depots

The feasibility of dry acid pretreatment used for decentralized pretreatment operation at biomass collection depots was evaluated. Crop residues biomass is dry acid pretreated, then biodetoxified to yield the dry powder morphology, inhibitor free biomass feedstock for simultaneous saccharification and ethanol co-fermentation (SSCF) (Fig. 2a). The ethanol titer achieved 85.1, 87.0, and 71.9 g/L (9.1–11.0%, v/v) using the typical crop residues biomass of corn stover, wheat straw and rice straw, respectively, with the yield of 215–260 kg of ethanol from one metric ton of biomass (dry base) (Liu and Bao, 2017a). As a comparison, AFEX uses liquid ammonia for fiber expansion pretreatment, then hydrolyze into fermentable sugars and co-ferment into ethanol with the similar overall yield of 205 kg of ethanol from one metric ton of biomass (Fig. 2b) (Uppugundla et al., 2014).

The scenarios of the two pretreatment methods, dry acid

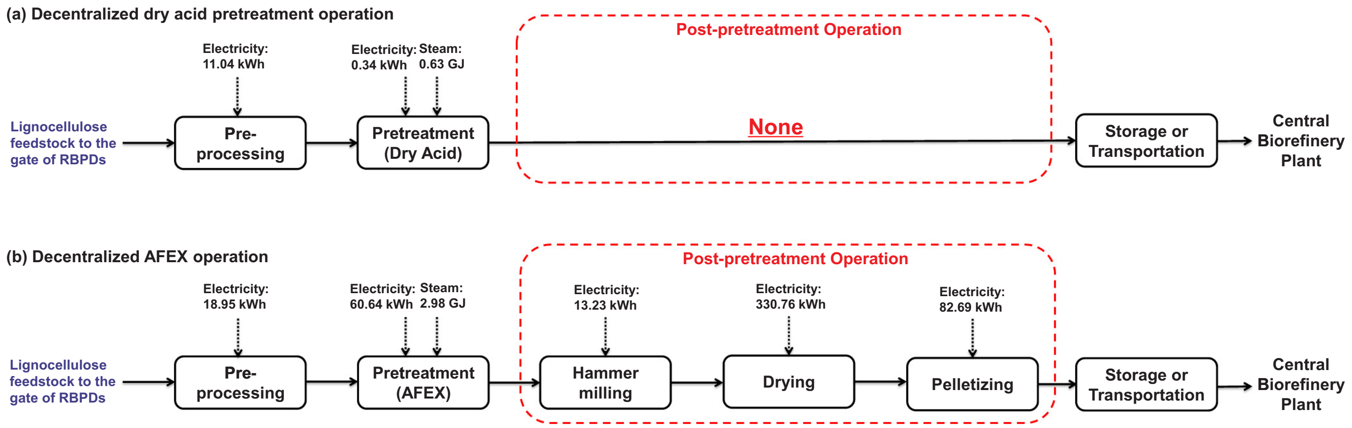


Fig. 3. Flowchart of decentralized pretreatment operation in biomass collection depots. (a) Decentralized dry acid pretreatment operation (Zhang et al., 2016b); (b) decentralized AFEX operation (Lamers et al., 2015).

pretreatment and AFEX, in the decentralized pretreatment at biomass collection depots were evaluated (Fig. 3). In the decentralized dry acid pretreatment operation at depots (Fig. 3a), crop residues biomass is preprocessed (de-ashed and grinded), dry acid pretreated, then either directly transported to the central biorefinery plant or stored for up to one year till use. In decentralized AFEX pretreatment operation (Fig. 3b), crop residues is AFEX pretreated, then post-pretreatment operations are required includes hammer milling, drying and pelletizing for increasing the volume density of pretreated biomass from 0.253 to 0.700 metric ton/m^3 (Table 1).

As the comparison, the post-pretreatment operation is not necessary for dry acid pretreatment operation because the tapped density of dry acid pretreated biomass (corn stover) has already reached to 0.743 metric ton/m^3 (Table 1). This density is 3.4 folds (dry basis) greater than the baling density of raw crop residues (0.117 metric ton/m^3 with 15% moisture) (Ma and Eckhoff, 2014). This property saves the energy consumption for ammonia recovery (64.64 kWh/metric ton), drying (82.69 kWh/metric ton), and pelletize (330.76 kWh/metric ton) used in AFEX pretreatment: 11.38 kWh of electricity and 0.63 GJ of steam in dry acid pretreatment vs. 506.27 kWh of electricity and 2.98 GJ of steam in AFEX pretreatment for processing one metric ton of dry feedstock. The capital investment of dry acid pretreatment system is also reduced to $3,323,090 from $8,215,488 of AFEX (Table 1).

3.2. Spatial distribution of crop residue biomass available for biorefining use in China and USA

The density distribution of the three major crop residues, corn stover, wheat straw and rice straw, in the mainland China (excluding Hong Kong, Macao and Taiwan) and the 48 states of USA (excluding Alaska and Hawaii) at the year of 2013 were calculated based on the crops data in the National Bureau of Statistics of China (www.stats.gov.cn/) and the US Department of Agriculture (www.nass.usda.gov), respectively. The weight ratio values (δ) of crop residues to grain are 1.25, 0.95 and 1.30 for corn, wheat and rice, respectively, according to the estimation by Qiu et al. (2014). The percentages (ε) of crop residues available for biorefining use in the total crop residues were 23–59%, varying with provinces in China (Qiu et al., 2014). In USA, the ε value was approximately calculated as 36.8% (Kim and Dale, 2015a).

Based on these statistics, the total annual production of corn stover, wheat straw and rice straw in China was estimated to be 653.68 million metric tons, and the amount available for biorefinery use was 249.98 million metric tons. Crop residues are mainly distributed in the East, Southcentral and Northeast China, where the four provinces of Jiangsu, Henan, Anhui and Jilin behave the maximum distribution density (177.18, 138.09, 117.71 and 109.38 metric tons/km^2, respectively). In USA, the total annual production of corn stover, wheat straw and rice straw was estimated to be 439.08 million metric tons and the amount available for biorefinery use was 176.83 million metric tons. The crop residues are mainly concentrated in the mid-west states, where Iowa, Illinois, Indiana, and Nebraska with the production of 163.18, 158.93, 124.56 and 91.28 metric tons/km^2, respectively. The distribution area of crop residues in USA is relatively concentrated and in favor of feedstock collection, in which corn stover is 161.58 million metric tons, accounting for 86.86% of the total available crop residues. On the other hand, the situation results in high pressure for collection and storage operation during short harvest period, and the long-term storage is urgently required for construct a supply chain to large scale biorefinery plants.

3.3. Potential of super large cellulosic ethanol plant in China and USA

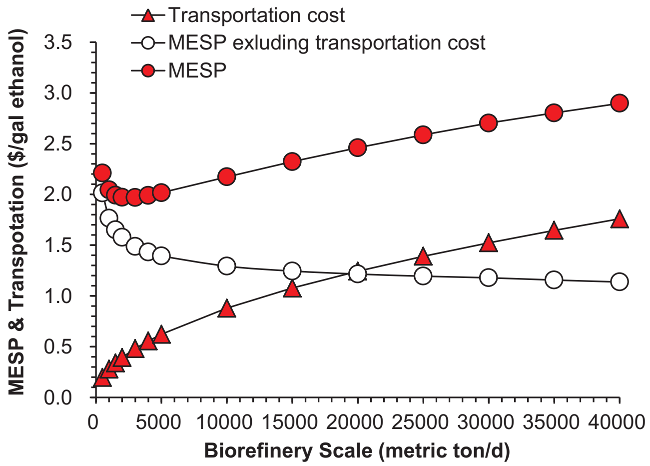
Different from general industrial operations, the overall cost of biorefinery processing increases dramatically with the increasing scale because of high transportation cost of traditional centralized biomass supply (Dale, 2017). The properties of dry acid pretreated biomass at depots provide a solution for reducing the transportation. In this study, the transportation and process cost of dry acid pretreatment operation at depots was evaluated varying biorefinery scale by taking Jilin province in northeast China as a base case. The unit purchase price (C_{pc}) of crop residues is estimated to be $12.9/metric ton, the road tortuosity factor (β) is 1.5 (Xing et al., 2008), the loss factor during transportation and storage (θ) is 4.94% (Suh et al., 2011), the collectable quantity of crop residues (α) is 109.38 metric ton/km^2, and the transport cost per unit distance for one unit volume cargo (P_v) is $0.07/(m^3·km) (Xing et al., 2008).

Fig. 4 shows that the transportation cost increases with the increasing of biorefinery scale, either the feedstock is collected by traditional centralized biomass supply or by decentralized biomass supply modes. If the transportation cost is excluded, the overall cost in term of minimum ethanol selling price (MESP) is reduced with increasing scale because of the economical efficient of scale. The final MESP is determined by the dual effects of the transportation cost and the MESP excluding transportation cost. The increase of transportation cost by the decentralized biomass supply is significantly weaker than that of the centralized biomass supply under the same biorefinery scale. For centralized biomass supply method (Fig. 4(a)), MESP decreases with increasing biorefinery scale when the biomass feedstock processing capability is below 2000 metric tons per day. However, MESP dramatically increases when the biorefinery scale is greater than 2000 metric tons/d because of the sharply increased transportation cost. The MESP is $1.97/gal at the economical biorefinery scale of 2000 metric tons/d with a collection radius of 44 km. For decentralized biomass supply method (Fig. 4(b)), MESP steadily decreases with increasing biorefinery

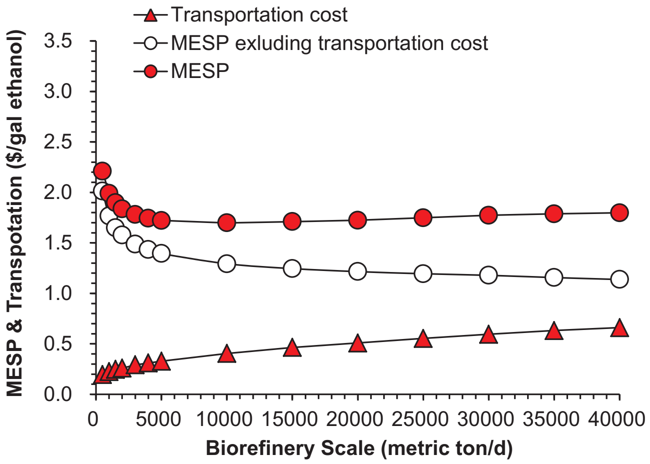
Table 1
Pretreatment technology choice for decentralized pretreatment operation at depot.

	Dry acid pretreatment[a]	AFEX pretreatment[b,c]
Temperature, pressure and residual time of pretreatment	175 °C, 0.89 MPa for 5 min	90 °C, 1.72 MPa for 30 min
Biomass collection depot scale (metric ton/day)	300[d]	200
Tapped density after pretreatment (metric ton/m^3)	0.743[e]	0.253
Solids content after pretreatment (metric ton/m^3)	46%	42%
Tapped density after pelletization (metric ton/m^3)	Not conducted	0.700
Solids content after pelletization (metric ton/m^3)	Not conducted	91%
Electricity consumption (kWh/metric ton)	11.38	506.27
Steam consumption[f] (GJ/metric ton)	0.63	2.98
Total capital investment ($)	3,323,090	8,215,488

[a] Zhang et al. (2016b).
[b] Lamers et al. (2015).
[c] Hoover et al. (2014).
[d] The cost-efficient scale of dry acid pretreatment based depots according the economic calculation.
[e] The tapped density measure method of dry acid pretreated biomass was according to Hoover et al. (2014).
[f] The heat supplied by steam which generated from natural gas boiler in both of pretreatments.



(a) Centralized biomass supply



(b) Decentralized biomass supply

Fig. 4. MESP and transportation cost as a function of biorefinery scale. (a) Centralized biomass supply; (b) decentralized biomass supply.

scale till the scale reaches 10,000 metric tons/d, then maintains almost constant with increasing plant scale because the cost increment from transportation almost balances the cost deduction from scale economies effect. When biorefinery scale increases from 10,000 metric tons/d to 40,000 metric tons/d, transportation cost increases from $0.41/gal to $0.66/gal, but the MESP only slightly increases from $1.70/gal to $1.80/gal. The economical biorefinery scale reaches 10,000 metric tons/d with the collection radius of 99 km and the corresponding MESP of $1.70/gal. These results suggest that the current decentralized dry acid pretreatment operation at depots overcomes the barrier of cost increase with increasing collection range. This result also leads to the conclusion that biorefinery plant size may increase to a super large scale at the reasonable cost increase of biomass feedstock on storage and transportation.

To construct a super large scale cellulosic ethanol plant equivalent to the average capability of petroleum refining plant (http://www.eia.gov/dnav/pet/pet_pnp_cap1_dcu_nus_a.htm), the biomass feedstock processing capability should be close to 30,000 metric tons daily, or 10.5 million metric tons annually (8410 operation hours, 350 working days annually). This processing capacity produces 703 million gal ethanol, or 2.1 million metric tons of fuel ethanol annually under the conservative estimation of one metric ton of ethanol from five metric tons of biomass feedstock (Liu and Bao, 2017a). The feasibility of super large cellulosic ethanol plant depends on two factors: biomass distribution density and the total collection area. The potential of super large cellulosic ethanol plants with the scale of 30,000 metric tons/d in China and USA were calculated in term of MESP and the biomass collection range. The calculation was based on the administrative basis of province level in China and state level in USA, in which the biomass distribution density is assumed to be uniformly distributed inside the calculation area. The current fuel ethanol average selling price of $2 per gal on the international fuel market in recent decade years was taken as the low threshold (http://www.tradingeconomics.com/commodity/ethanol).

In China, six provinces (Jiangsu, Henan, Anhui, Jilin, Shandong and Hunan) are capable of constructing super large scale cellulosic ethanol plants (30,000 metric tons of biomass feedstock processing capability daily) with the MESP below $2/gal ($1.56, $1.66, $1.72, $1.77, $1.94, and $1.98 per gal, respectively). The biomass distribution density of Jiangsu province requires an area of 56,440 km^2 with the radius of 134 km to collect biomass feedstock for one super large scale cellulosic ethanol plant construction. Therefore, approximately two super large cellulosic ethanol plants are feasible in Jiangsu (the total administrative area is 102,600 km^2). Henan, Jilin, and Hunan provinces are also capable of constructing two super large scale cellulosic ethanol plants, and Anhui and Shandong provinces are capable of one with the collection radius of 152–199 km. In USA, four midwest states (Iowa, Illinois, Indiana and Nebraska) are capable of constructing one super large scale cellulosic ethanol plants with the MESP below $2/gal ($1.58, $1.60, $1.69, and $1.90 per gal, respectively) and the biomass collection radiuses are 140, 142, 160 and 187 km, respectively.

This calculation basis is certainly rough because the collection area of crop residues should be based on the agriculture properties, instead of administrative boundaries with diverse biomass output insides. More accurate calculation on the smaller county or town levels could provide more feasible diagram for super large scale biorefinery planning. An example is Heilongjiang province in China with the collect area of 130,693 km^2 and the radius of 204 km to give the MESP of $2.02/gal, slight above the threshold cost of $2/gal. Construction of one or two super large scale plants with the MESP below $2/gal is highly possible in Heilongjiang province if the administrative boundary is broken and more nearby land is embodied. Unfortunately, currently the agriculture statistic data are not available at the county or town levels both in China and USA. Even so, the present calculation on province or state level provides the solid calculation methodology for super large cellulosic ethanol plants and easily extends to a fine calculation with the input of detailed geographical agriculture statistics.

4. Conclusion

Dry acid pretreatment provides a suitable option for decentralized pretreatment operation at biomass collection depots. This method not only significantly reduces transportation cost and the overall MESP, but also overcomes the barrier of cost increase with increasing collection range. This operation made the construction of super large scale cellulosic ethanol plants equivalent to the capacity of intensive petroleum refining plant to be a possible option with the MESP below $2/gal in agricultural provinces or states of China and USA.

Acknowledgement

This research was supported by the Natural Science Foundation of China (NSFC) 3181101658, the National Basic Research Program of China (2011CB707406), the China Postdoctoral Science Foundation (2018M632043), the Fundamental Research Funds for the Central Universities of China (WF1814033), and the Open Funding Project of the Key Laboratory of Development and Application of Rural Renewable Energy.

Appendix A. Supplementary data

E-supplementary data of this work can be found in online version of the paper. Annual output of main crops and crop residues of China and USA in 2013 were shown in Table A.1 and Table A.2, respectively. General flowsheet of DryPB biorefining process for cellulosic ethanol production on Aspen plus platform were shown in Fig. A.1. Distribution density of crop residues available for biorefinery use in China and USA were shown in Fig. A.2. MESP of cellulosic ethanol plant with capacity of processing 30,000 metric ton biomass per day in China and USA were shown in Fig. A.3. Supplementary data to this article can be found online at https://doi.org/10.1016/j.biortech.2018.12.061.

References

Aden, A., Ruth, M., Ibsen, K., Jechura, J., Neeves, K., Sheehan, J., Wallace, B., Montague, L., Slayton, A., Lukas, J., 2002. Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. NREL/TP-510-32438. National Renewable Energy Laboratory, Golden, CO.

Bals, B.D., Dale, B.E., 2012. Developing a model for assessing biomass processing technologies within a local biomass processing depot. Bioresour. Technol. 106, 161–169.

Bals, B.D., Gunawan, C., Moore, J., Teymouri, F., Dale, B.E., 2014. Enzymatic hydrolysis of pelletized AFEX™-treated corn stover at high solid loadings. Biotechnol. Bioeng. 111, 264–271.

Chen, X., Kuhn, E., Jennings, E.W., Nelson, R., Tao, L., Zhang, M., Trker, M.P., 2016. DMR (deacetylation and mechanical refining) processing of corn stover achieves high monomeric sugar concentrations (230 g L^{-1}) during enzymatic hydrolysis and high ethanol concentrations (> 10% v/v) during fermentation without hydrolysate purification or concentration. Energy Environ. Sci. 9, 1237.

Dale, B., 2017. A sober view of the difficulties in scaling cellulosic biofuels. Biofuels Bioprod. Bioref. 11, 5–7.

Eranki, P.L., Bals, B.D., Dale, B.E., 2011. Advanced regional biomass processing depots: a key to the logistical challenges of the cellulosic biofuel industry. Biofuels Bioprod. Bioref. 5, 621–630.

Gonzales, D., Searcy, E.M., Eksioglu, S.D., 2013. Cost analysis for high-volume and long-haul transportation of densified biomass feedstock. Trans. Res. A-Pol. 49, 48–61.

He, Y., Zhang, L., Zhang, J., Bao, J., 2014a. Helically agitated mixing in dry dilute acid pretreatment enhances the bioconversion of corn stover into ethanol. Biotechnol. Biofuels 7, 1.

He, Y., Zhang, J., Bao, J., 2014b. Dry dilute acid pretreatment by co-currently feeding of corn stover feedstock and dilute acid solution without impregnation. Bioresour. Technol. 158, 360–364.

He, Y., Zhang, J., Bao, J., 2016. Acceleration of biodetoxification on dilute acid pretreated lignocellulose feedstock by aeration and the consequent ethanol fermentation evaluation. Biotechnol. Biofuels 9, 19.

Hess, J.R., Wright, C.T., Kenney, K.L., 2007. Cellulosic biomass feedstocks and logistics for ethanol production. Biofuel Bioprod. Bioref. 1, 181–190.

Hoover, A.N., Tumuluru, J.S., Teymouri, F., Moore, J., Gresham, G., 2014. Effect of pelleting process variables on physical properties and sugar yields of ammonia fiber expansion pretreated corn stover. Bioresour. Technol. 164, 128–135.

Huang, C., Wu, X., Huang, Y., Lai, C., Li, X., Yong, Q., 2016. Prewashing enhances the liquid hot water pretreatment efficiency of waste wheat straw with high free ash content. Bioresour. Technol. 219, 583–588.

Humbird, D., Davis, R., Tao, L., Kinchin, C., Hsu, D., Aden, A., Schoen, P., Lukas, J., Olthof, B., Worley, M., Sexton, D., Dudgeon, D., 2011. Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol. NREL/TP-5100-47764. National Renewable Energy Laboratory, Golden, CO.

Karlen, D.L., Birell, S.J., Hess, J.R., 2011. A five-year assessment of corn stover harvest in central Iowa U.S.A. Soil Till. Res. 115, 47–55.

Kim, S., Dale, B.E., 2015a. Comparing alternative cellulosic biomass biorefining systems: centralized versus distributed processing systems. Biomass Bioenergy 74, 135–147.

Kim, S., Dale, B.E., 2015b. All biomass is local: The cost, volume produced, and global warming impact of cellulosic biofuels depend strongly on logistics and local conditions. Biofuels Bioprod. Bioref. 9, 422–434.

Kim, J.S., Lee, Y.Y., Kim, T.H., 2016. A review on alkaline pretreatment technology for bioconversion of lignocellulosic biomass. Bioresour. Technol. 199, 42–48.

Ko, J.K., Kim, Y., Ximenes, E., Ladisch, M.R., 2015. Effect of liquid hot water pretreatment severity on properties of hardwood lignin and enzymatic hydrolysis of cellulose. Biomass Bioenergy 112 (2), 252–262.

Kocoloski, M., Griffin, W.M., Matthews, H.S., 2011. Impacts of facility size and location decisions on ethanol production cost. Energy Policy 39, 47–56.

Konda, N.M., Shi, J., Singh, S., Blanch, H.W., Simmons, B.A., Klein-Marcuschamer, D., 2014. Understanding cost drivers and economic potential of two variants of ionic liquid pretreatment for cellulosic biofuel production. Biotechnol. Biofuels 7, 86.

Kumar, A., Sokhansanj, S., 2007. Switchgrass (Panicum vigratum, L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. Bioresour. Technol. 98, 1033–1044.

Lamers, P., Roni, M.S., Tumuluru, J.S., Jacobson, J.J., Cafferty, K.G., Hansen, J.K., Kenney, K., Teymouri, F., Bals, B., 2015. Techno-economic analysis of decentralized biomass processing depots. Bioresour. Technol. 194, 205–213.

Lin, T., Rodriguez, L.F., Shastri, Y.N., Hansen, A.C., Ting, K.C., 2014. Integrated strategic and tactical biomass–biofuel supply chain optimization. Bioresour. Technol. 156, 256–266.

Liu, G., Bao, J., 2017b. Evaluation of electricity generation from lignin residue and biogas in cellulosic ethanol production. Bioresour. Technol. 243, 1232–1236.

Liu, G., Bao, J., 2017a. Maximizing cellulosic ethanol potentials by minimizing wastewater generation and energy consumption: competing with corn ethanol. Bioresour. Technol. 244, 1188–1192.

Liu, G., Bao, J., 2018. Dry biorefining maximizes the potentials of simultaneous saccharification and co-fermentation for cellulosic ethanol production. Biotechnol. Bioeng. 102, 377–388.

Lloyd, T.A., Wyman, C.E., 2005. Combined sugar yields for dilute sulfuric acid pretreatment of corn stover followed by enzymatic hydrolysis of the remaining solids. Bioresour. Technol. 96, 1967–1977.

Lu, X., Withers, M.R., Seifkar, N., Field, R.P., Barrett, S.R.H., Herzog, H.J., 2015. Biomass logistics analysis for large scale biofuel production: case study of loblolly pine and switchgrass. Bioresour. Technol. 183, 1–9.

Lynd, L.R., Liang, X., Biddy, M.J., ALLee, A., Cai, H., Foust, T., Himmel, M.E., Laser, M.S., Wang, M., Wyman, C.E., 2017. Cellulosic ethanol: status and innovation. Curr. Opin. Biotech. 45, 202–211.

Ma, S., Eckhoff, S.R., 2014. Economy of scale for biomass refineries: bulk densities, transportation cost, and producer incentives. T. ASABE 57, 85–91.

Martelli, R., Bentini, M., 2015. Harvest storage and handling of round and square bales of giant reed and switchgrass, an economic and technical evaluation. Biomass Bioenergy 73, 67–76.

Mora-Pale, M., Meli, L., Doherty, T.V., Linhardt, R.J., Dordick, J.S., 2011. Room temperature ionic liquids as emerging solvents for the pretreatment of lignocellulosic biomass. Biomass Bioenergy 108 (6), 1229–1245.

Qiu, H.G., Sun, L.X., Xu, X.L., Cai, Y.Q., Bai, J.F., 2014. Potentials of crop residues for commercial energy production in China: a geographic and economic analysis. Biomass Bioenergy 64, 110–123.

Saha, B.C., Iten, L.B., Cotta, M.A., Wu, Y.V., 2005. Dilute acid pretreatment, enzymatic saccharification and fermentation of wheat straw to ethanol. Process Biochem. 40, 3693–3700.

Shao, S., Zhang, J., Bao, J., 2017. Reduction of reactor corrosion by eliminating liquid-phase existence in dry dilute acid pretreatment of corn stover. Energy Fuel 31 (6), 6140–6144.

Sokhansanj, S., Mani, S., Tagore, S., Turhollow, A.F., 2010. Techno-economic analysis of using corn stover to supply heat and power to a corn ethanol plant – part 1: cost of feedstock supply logistics. Biomass Bioenergy 34, 75–81.

Suh, K., Suh, S., Walseth, B., Bae, J., Barker, R., 2011. Optimal corn stover logistics for biofuel production: a case in Minnesota. T. ASABE 54, 229–238.

Tembo, G., Epplin, F.M., Huhnke, R.L., 2003. Integrative investment appraisal of a lignocellulosic biomass-to-ethanol industry. J. Agric. Resour. Econ. 28, 611–633.

Uppugundla, N., Sousa, L.C., Chundawat, S.P.S., Yu, X., Simmons, B., Singh, S., Gao, X., Kumar, R., Wyman, C.E., Dale, B.E., Blan, V., 2014. A comparative study of ethanol production using dilute acid, ionic liquid and AFEX™ pretreated corn stover. Biotechnol. Biofuels 7, 72.

Xing, A.H., Liu, G., Wang, Y., Wei, F., Jin, Y., 2008. Economic, energy and environment analysis on biomass collection process (in Chinese). Chin. J. Process Eng. 8, 305–313.

Zhang, J., Zhu, Z., Wang, X., Wang, N., Wang, W., Bao, J., 2010. Biodetoxification of toxins generated from lignocellulose pretreatment using a newly isolated fungus *Amorphotheca resinae* ZN1 and the consequent ethanol fermentation. Biotechnol. Biofuels 3, 26.

Zhang, J., Wang, X., Chu, D., He, Y., Bao, J., 2011. Dry pretreatment of lignocellulose with extremely low steam and water usage for bioethanol production. Bioresour. Technol. 102, 4480–4488.

Zhang, J., Shao, S., Bao, J., 2016b. Long term storage of dilute acid pretreated corn stover feedstock and ethanol fermentability evaluation. Bioresour. Technol. 201, 355–359.

Zhang, J., Hou, W., Bao, J., 2016a. Reactors for high solid loading pretreatment of pretreatment of lignocellulosic biomass. Adv. Biochem. Eng. Biotechnol. 152, 75–90.