Impacts of uncertain feedstock quality on the economic feasibility of fast pyrolysis biorefineries with blended feedstocks and decentralized preprocessing sites in the Southeastern United States

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Abstract
This study performs techno-economic analysis and Monte Carlo simulations (MCS) to explore the effects that variations in biomass feedstock quality have on the economic feasibility of fast pyrolysis biorefineries using decentralized preprocessing sites (i.e., depots that produce pellets). Two biomass resources in the Southeastern United States, that is, pine residues and switchgrass, were examined as feedstocks. A scenario analysis was conducted for an array of different combinations, including different pellet ash control levels, feedstock blending ratios, different biorefinery capacities, and different biorefinery on-stream capacities, followed by a comparison with the traditional centralized system. MCS results show that, with depot preprocessing, variations in the feedstock moisture and feedstock ash content can be significantly reduced compared with a traditional centralized system. For a biorefinery operating at 100% of its designed capacity, the minimum fuel selling price (MFSP) of the decentralized system is $3.97–$4.39 per gallon gasoline equivalent (GGE) based on the mean value across all scenarios, whereas the mean MFSP for the traditional centralized system was $3.79–$4.12/GGE. To understand the potential benefits of highly flowable pellets in decreasing biorefinery downtime due to feedstock handling and plugging problems, this study also compares the MFSP of the decentralized system at 90% of its designed capacity with a traditional system at 80%. The analysis illustrates that using low ash pellets mixed with switchgrass and pine residues generates a more competitive MFSP. Specifically, for a biorefinery designed for 2,000 oven dry metric ton per day, running a blended pellet made from 75% switchgrass and 25% pine residues with 2% ash level, and operating at 90% of designed capacity could make an MFSP between $4.49 and $4.71/GGE. In contrast, a traditional centralized biorefinery operating at 80% of designed capacity marks an MFSP between $4.72 and $5.28.
1 | INTRODUCTION

Biofuels have attracted considerable interest over the past three decades as alternatives to traditional fossil fuels to reduce environmental burdens and ensure energy security (Cervi et al., 2020; Correa et al., 2019; De La Torre Ugarte et al., 2007; Kumar et al., 2018; Lask et al., 2019; Peckham & Gower, 2013; Sanz Requena et al., 2011; Whitaker et al., 2010). The U.S. Renewable Fuel Standard has a target of 16 billion gallons of cellulosic biofuel by 2022, which would account for 44% of total renewable fuels supplies (US EPA, 2019). The rapid expansion of a commercial biofuel industry requires the delivery of consistent biomass feedstock in sufficient quantity, at a feasible cost, and with uniform quality (Lamers et al., 2015). Relying on a single source of biomass feedstock can limit the size of biorefineries with centralized preprocessing because of biomass availability and high biomass transportation costs (He-Lambert et al., 2018; Lan et al., 2019). Variations in supply chain operations (e.g., logistics and biomass supply) and variations in feedstock composition (e.g., carbon, moisture, and ash content) have a substantial negative impact on the performance of the biorefinery (Kazemzadeh & Hu, 2013; Kim et al., 2011; Li & Hu, 2014). In addition, operational problems with feeding systems, size reduction, drying, screening and feeding can potentially influence biorefinery productivity (Westover & Hartley, 2018). For example, problems due to bridging and rat-holing can cause inefficiencies with operations such as transfer from storage bins, particularly when feeding into a high-pressure environment (Dai et al., 2012; Miccio et al., 2013). Experience from the pellet industry has shown that high-density pellets alleviate many of these problems (Lamers et al., 2015; Tumuluru, 2019). Blending biomass feedstocks and using decentralized preprocessing sites (so-called depots) can also reduce the delivered cost and increase overall feedstock quality (Edmunds et al., 2018; Kenney et al., 2014; Kenney et al., 2013; Lamers et al., 2015; Thompson et al., 2013; Wells et al., 2016). At a decentralized depot, biomass feedstocks are preprocessed to produce flowable pellets that have a uniform moisture content (MC) and composition, which can then be transported to the biorefinery for biofuel production (Lamers et al., 2015). Decentralized supply depots can reduce travel distances for raw and higher MC biomass and can allow for the production of low-moisture, high-density pellets that can be efficiently transported over longer distances. Understanding the economic drivers for decentralized depots to preprocess blended biomass, and how variations in biomass feedstock supply and composition affect supply chain performance, is critical for developing the large-scale biofuel industry.

In this study, the techno-economic analysis (TEA) was used to assess the economic feasibility of two biorefinery systems (traditional centralized system vs. decentralized depot system) using two biomass feedstocks—forest residues and switchgrass (Patel et al., 2016; Sorummu et al., 2020). TEA of biofuel production has been applied to alternative biomass conversion technologies and biomass feedstock types (Beal et al., 2015; Bridgewater et al., 2002; Dang et al., 2018; Dimitriou et al., 2018; Dutta et al., 2011, 2015; Klein-Marcuschamer et al., 2011; Kumaravel et al., 2012; Mohsenzadeh et al., 2017; Patel et al., 2016; Pfommm et al., 2010; Pirraglia et al., 2010; Sahoo et al., 2019; Segurado et al., 2019; Swanson, Platon, Satrio, & Brown, 2010; Tao et al., 2017; Wright, Daugaard, Brown, & Satrio, 2010). For example, Wright et al. (2010) investigated the economic feasibility of fast pyrolysis biofuel from corn stover with two scenarios: one used onsite hydrogen generation from bio-oil and the other used merchant hydrogen from natural gas reforming for its upgrade. They showed that the biofuel product value was $3.09 per gallon gasoline equivalent (GGE) for the first scenario and $2.11 for the second scenario (Wright et al., 2010). Swanson et al. (2010) evaluated the product value of biofuel by gasification and Fischer–Tropsch synthesis from corn stover, reporting that the product value ranged from $4 to $5/GGE. Thilakaratne et al. (2014) applied TEA to a 2,000 metric ton per day biorefinery producing biofuel from poplar via catalytic pyrolysis, and they calculated the minimum fuel selling price (MFSP) as $3.69/GGE.

Most previous studies focused on the traditional centralized system rather than a decentralized system with blended biomass feedstocks. Researchers have explored the supply chain performance of either decentralized systems (Hiloidhari et al., 2017; Iglesias et al., 2012; Kesharwani et al., 2019; Kim et al., 2019; Lamers et al., 2015; Roostaei & Zhang, 2017; You & Wang, 2011) or blended biomass feedstocks (Akgul et al., 2012; Ren et al., 2016; You & Wang, 2011), but there has been neither a systematic study of these alternatives in combination nor did these previous studies address the effects of variable feedstock quality and biorefinery performance on the economic performance of two different systems under varied facility capacities and blending ratios. To fully understand the benefits of using the decentralized system, it is necessary to understand how a depot (a biomass preprocessing site) that blends and densifies biomass into low-moisture pellets impacts the economic feasibility of the biorefinery given...
variations in biomass feedstock characteristics (i.e., carbon, moisture, and ash content) and biorefinery operations (overall biorefinery actual performance).

To address this knowledge gap, this study uses TEA to analyze the MFSP of biofuel produced via a fast pyrolysis biorefinery using blended biomass operating in the southeastern United States. Two common biomass feedstocks for the southeastern United States were studied, that is, pine residues and switchgrass. In the United States, forest residues generated from thinning and logging provide abundant renewable resources (Perlack et al., 2011) but are currently either left on site for decay or burnt for site preparation without productive use of their energy (Hubbert et al., 2013; Jones et al., 2010). Collecting and converting pine residues to high-value biofuel products can potentially provide additional revenue to landowners, reduce wildfire risks, and produce biofuel to replace fossil fuels, thus mitigating greenhouse gas emissions (Han et al., 2018; He et al., 2016; Page-Dumroese et al., 2017; Sahoo et al., 2019). Switchgrass in the Southeastern United States is commonly identified as a promising energy crop for biofuel production (Bai et al., 2010; Cundiff & Marsh, 1996; Larson et al., 2010; McLaughlin et al., 1999; Ney & Schnoor, 2002; Sanderson et al., 2011; Yu et al., 2016).

In this study, Monte Carlo simulation (MCS) was used to model variations in feedstock composition and overall biorefinery performance (Awudu & Zhang, 2013; Kim et al., 2011; Peters, 2007). Scenario analysis was conducted to evaluate the corresponding effects on MFSP under different system configurations (traditional or decentralized), pellet ash levels, blending ratios, and biorefinery capacities. The mass and energy balance for TEA was derived from process-based simulations for the depot and biorefinery.

2 MATERIALS AND METHODS

Schematic diagrams for the traditional centralized system and the decentralized system are shown in Figure 1. In this study, pine residues were generated by thinning and logging, and then collected and chipped on the forest site. Switchgrass was harvested and packaged in large rectangular bales for transport to preprocessing (Larson et al., 2015). For the traditional centralized system shown in Figure 1a, biomass feedstocks were directly transported to the biorefinery to produce biofuel (including feedstock pretreatment inside the biorefinery). Hence, the delivered cost for the traditional centralized system only included the cost of biomass production, harvest, and transportation cost. The MC for the pine residues and switchgrass during this transportation stage averaged 50.1% average (ranging between 35.0% and 69.2%) and 14.8% (ranging between 8.4% and 22.0%), respectively. For the decentralized system shown in Figure 1b, biomass feedstocks with the same MC as defined above were first transported to the depot for preprocessing. Depot preprocessing activities included size reduction, drying, and densification resulted in pellets with 9% MC (wb). Pellets were then transported to the biorefinery by secondary transportation. The delivered cost for the decentralized system included the cost of biomass production, transportation cost (initial and secondary), and the capital and operating cost of biomass preprocessing at the depot.

In this study, the commonly adopted economic indicator, MFSP, was used to gauge the economic feasibility for biofuel production (Dutta et al., 2015; Jones et al., 2013; Tao et al., 2017). The MFSP of biofuel was derived through the discounted cash flow rate of return (DCFROR) analysis (Humbird et al., 2011; Ou et al., 2018; Sahoo et al., 2019; Swanson et al., 2010; Wright et al., 2010). Probability distributions for feedstock composition, biorefinery scale, and biorefinery performance were based on an extensive analysis of the literature data (see Sections 2.1 and 2.3). The cost of biomass production (pine residues and switchgrass) was based on previous literature (see Section 2.1). The transportation cost data were evaluated based on a Geographic Information System, BioFLAME, analyzing the biomass availability, transportation distance, and facility locations (English et al., 2013; Larson et al., 2015) and were documented in the authors’ previous publication (see Section S1; Lan et al., 2020).
The cost of depot preprocessing and biorefinery processing was calculated based on the mass and energy balance from the process-based simulation models reported in our previous studies (Lan et al., 2019; Ou et al., 2018).

2.1 | Biomass production and compositions

In this study, pine residues were collected from thinning (precommercial or commercial) and final harvest, including the limbs, tops, and small diameter trees (Lacey et al., 2015). Residues were then chipped onsite in the forest and transported in chip vans to their next destination. Variations in the pine residue compositions were evaluated, including the carbon content, MC, and ash content. The carbon content of pine residues can vary depending on many parameters, including the tree species (e.g., loblolly pine), forest site, residue component (e.g., wood, bark or needles), and tree age (Huang et al., 2011; Laiho & Laine, 1997; Schultz, 1997). Variations in the carbon content of pine residues were obtained from the literature and analyzed to make assumptions concerning the distribution, as listed in Table 1. The MC of

| TABLE 1 | Statistical distribution of biomass compositions |
|----------|-----------------------------------------------|
| **Unit** | **Mean** | **Minimum** | **Maximum** | **Assumed distribution** | **References** |
| Pine residue carbon content | %dry | 49.2 | 45.5 | 52.0 | Normal N (49.2, 2^2) | Casal et al. (2010), Chen et al. (2015), Daystar et al. (2012), Ferreiro et al. (2017), López-González et al. (2013), López et al. (2013), Phanphanich and Mani (2010, 2011), Silva and Rouboa (2013), Wang et al. (2014), Westbrook Jr. et al. (2007), Zacher et al. (2014) |
| Pine residue MC | %wet | 50.1 | 35.0 | 69.2 | Normal N (50.1, 9.3^2) | Casal et al. (2010), Das et al. (2011), Daystar et al. (2012), Erber et al. (2012), Filbakk et al. (2011), Oasmaa et al. (2003), Phanphanich and Mani (2011), Westbrook Jr. et al. (2007) |
| Pine residue ash content | %dry | 1.42 | 0.40 | 3.60 | Gamma a = 3.50, b = 0.470 | Casal et al. (2010), Chen et al. (2015), Das et al. (2011), Daystar et al. (2012), Ferreiro et al. (2017), Huang et al. (2011), Kenney et al. (2013), Lacey et al. (2015), López et al. (2013), López-González et al. (2013), Phanphanich and Mani (2010, 2011), Silva and Rouboa (2013), Someshwar (2010), Wang et al. (2014), Zacher et al. (2014) |
| Switchgrass carbon content | %dry | 46.1 | 41.3 | 49.7 | Normal N (46.1, 2.1^2) | Boateng et al. (2007), Brummer et al. (2002), Carpenter et al. (2010), Chen et al. (2016), Dayton et al. (1995), Edmunds et al. (2018), Fahmi et al. (2007), Habibi et al. (2013), Imam and Capareda (2012), Lemus et al. (2002), Masnadi et al. (2015a, 2015b), Moutsoglou (2012), Ogden et al. (2010), Pilon and Lavoie (2011), Sharma et al. (2011), Vamvuka et al. (2010), Wang et al. (2015), Yang et al. (2014) |
| Switchgrass MC | %wet | 14.8 | 8.4 | 22.1 | Uniform [8.4,22.1] | Cundiff and Marsh (1996), Elbersen et al. (2000), Imam and Capareda (2012), Kenmerer and Liu (2010), Khanchi et al. (2013), Khanna et al. (2008), Kumar and Sokhansanj (2007), Masnadi et al. (2015a), McLaughlin et al. (1999), Monti et al. (2009), Ogden et al. (2010), Sahoo and Mani (2016), Sanderson et al. (1997), Sharma et al. (2011), Sokhansanj et al. (2009), Womac et al. (2012), Yang et al. (2014) |
| Switchgrass ash content | %dry | 4.3 | 1.2 | 10.2 | Gamma a = 2.5, b = 1.5 | Boateng et al. (2007), Brummer et al. (2002), Carpenter et al. (2010), Casler and Boe (2003), Chen et al. (2016), Dayton et al. (1995), Edmunds et al. (2018), Elbersen et al. (2000), Ewanick and Bura (2011), Fahmi et al. (2007), Habibi et al. (2013), He et al. (2009), Imam and Capareda (2012), Lemus et al. (2002), Liu and Bi (2011), Mani et al. (2004), Masnadi et al. (2015a, 2015b), McLaughlin et al. (1999), Moutsoglou (2012), Ogden et al. (2010), Pilon and Lavoie (2011), Sadaka et al. (2014), Sharma et al. (2011), Vamvuka et al. (2010), Wang et al. (2015), Wiselogel et al. (1996), Yan et al. (2010), Yang et al. (2014) |
forest residues is largely dependent on the components, site conditions, weather, and storage conditions. For example, Westbrook et al. (2007) reported that the MC of residues for tops and limbs from different sampling blocks in Georgia, United States, ranged from 46.2% to 51.9% while the MC of residues for tops, limbs, and understory varied from 29.6% to 46.8%. Filbakk et al. (2011) identified that the logging residues harvested in the 2007/2008 winter season had significantly higher MC than those harvested in the 2008 spring season. Das et al. (2011) reported the mean MCs of precommercial thinning residues, pine top residues, and pine top and understory residue values of 45.9%, 43.4%, and 37.7%, respectively. Unlike the biochemical conversion process, a fast pyrolysis reaction always requires a feedstock with less than 10% MC (Ringer et al., 2006). Hence, feedstocks at higher MCs lead to the high cost in terms of the energy consumed to dry the biomass. We assumed MC distributions for pine residues out of a forest site based on literature data, as listed in Table 1.

Ash content is another significant source of variation for most biomass feedstocks. There are two types of biomass ash. One is entrained ash that represents soil entrained by the biomass during harvesting and processing. Entrained ash can be largely reduced by adopting best management practices and operations, as well as mechanical separations (Reza et al., 2015). The second source is structural ash, representing the physiological-bound minerals in the biomass structure, which is difficult to remove. Table 1 also lists the ash content data for pine residues.

Switchgrass is harvested and baled on site. Similar to pine residues, the switchgrass carbon, moisture, and ash content data were collected from the literature (Table 1). The MC of switchgrass bales is heavily dependent on the harvesting season and local weather, bale type (e.g., round or rectangular), storage type (e.g., tarped or not, storage barn), and storage conditions (e.g., rainfall and air humidity) (Khanchi et al., 2013; Mooney et al., 2012; Wiselogel et al., 1996; Yu et al., 2015). For example, Khanchi et al. (2013) monitored the MC change and dry matter loss associated with storing switchgrass bales under varied conditions. They reported lower moisture accumulation for tarped bales (e.g., 8%–13% wb for tarped round bales) compared with un tarped bales (e.g., 14%–22% wb for un tarped round bales). Furthermore, higher MC values were observed for tarped bales stored outside (13.5% wb in 2010) on the ground compared with bales stored inside (8.9% wb in 2010). Significantly high moisture accumulation was observed for un tarped square bales (48%–62% wb) compared with un tarped round bales (14%–22% wb) (Khanchi et al., 2013). At the same time, the switchgrass ash content can vary over a wide range based on different sites, management strategies, and harvesting operations. Table 1 also lists the distributions of switchgrass ash content.

To account for the cost of biomass production, the pine residue and switchgrass costs were assumed to be $34 and $64 per oven dry metric ton (ODMT), respectively. The detailed calculation for the cost of biomass production can be found in Lan et al. (2020).

2.2 Depot preprocessing

In this study, the high moisture pelleting process (HMPP), as proposed by the U.S. Idaho National Laboratory (INL) (Kenney et al., 2014) and Lamers et al. (2015), was used as the preprocessing technology in the depot. These studies report energy and cost savings relative to the conventional pelleting process (Lan et al., 2020). The primary task for the depot is to reduce the feedstock size and MC, as well as to produce pellets at low MC (9% wb) characterized by more effective transport and handling. Based on prior studies, the depot capacity was fixed at 500 ODMT/day (Lan et al., 2020). Four different biomass blending options were selected, that is, 100%, 75%, 50%, and 25% pine residues (dry weight basis), with the balance composed of switchgrass.

Excessive ash in the biomass pellets can cause ash slagging, agglomeration, fouling, corrosion in the chamber, and harm the biofuel yield per ODMT basis (Kenney et al., 2013; Tabil et al., 2011; Tarasov et al., 2013; Toscano et al., 2013; Vermont Grass Energy Partnership, 2011). Currently, there are several published standards for the ash content level of biomass pellets (García-Maraver et al., 2011). For example, the European Standard Committee CEN/TC 335 published the standard for solid fuel, including wood pellets, and classified the ash content into several levels (e.g., ≤0.7%, ≤1.5%, ≤3%, and ≤6%) (European Committee for Standardization, 2004; García-Maraver et al., 2011). The EN 14961-2 classifies the pellet ash content into A1 (≤0.7%), A2 (≤1.5%), and B (≤3.5%) categories (Duca et al., 2014). The U.S. based Pellet Fuel Institute (PFI) requires the pellet ash contents for the PFI Premium grade at less than 1%, PFI Standard at 2%, and PFI Utility at 6% (PFI, 2010). There are two common methods for lowering the pellet ash content. One is to reduce entrained ash by adopting feedstock pre-selection, best management practices in harvesting (e.g., optimal cut height), collecting, handling, and onsite trommel screening (Kenney et al., 2013, 2014). The other one is controlling structural ash by selecting the plant maturity for harvest and choosing proper fertilization practices (Adler et al., 2006; Davidsson et al., 2002). Due to the lack of data on the additional cost of controlling feedstock ash in literature, this study does not assume an additional cost for low-ash cases. Instead, this study focused on understanding the consequential effects of applying ash content control standards at the depot on the final MFSP. However, investigating the costs of ash control in biomass production could
be a future research direction and the results of this study can be used by researchers as a basis for future economic analysis. In this study, the deashing level cases followed the current published standards and were assumed to be <3, <2, and <1%.

Figure 2 shows the process flows for the HMPP process modeled in this study for 100% pine residues and blended biomass feedstock. The major unit operations in Figure 2 are based on our previous study and are briefly discussed as follows (Lan et al., 2019).

The HMPP as proposed by the U.S. INL uses a two-stage grinding and fractional milling process (Kenney et al., 2014). First stage grinding for pine residues after collection in the forest involves chipping residues at the roadside into 152 mm (6 inches) average particle sizes before materials are transported for further processing. Before the second stage grinding process, pine residues are predried to 30% (wb) using a rotary drum dryer. For switchgrass, the first stage uses the bale grinder at the depot to reduce feedstock to 152 mm particles. For both feedstocks, the second stage grinding uses the hammer mill to reduce the size to 2.5–3.8 mm. In fractional milling, a screener separator is used after the first stage grinding. If the materials pass the screener, the operator can then bypass the second-stage grinding process for this fraction of the feedstock. Using this technique, 47%–53% of the materials can bypass the second-stage grinding (Kenney et al., 2014). After grinding, biomass is pelleted and cooled (Lamers et al., 2015). The durable, loosely packed pellets allow the use of a cross-flow grain dryer operating at low temperature (80°C), which further dries the pellets to the final 9% (wb) MC target.

The energy and mass balance of each unit operation and preprocessing cost (including capital, energy, labor, repair and maintenance, insurance, housing, and tax) were modeled and documented in our previous studies (more details available in Section S2) (Lan et al., 2019).

### 2.3 Biorefinery processing

The cost analysis of the biomass conversion at biorefineries was based on the process simulation models developed in ASPEN Plus (Ou et al., 2018). Figure 3 shows the system diagram of the fast pyrolysis biorefinery in the traditional centralized system and the decentralized system. In the traditional centralized system, the pretreatment is conducted inside the biorefinery. In pretreatment, biomass feedstocks are dried in the rotary drum dryer after initial grinding. Then the hammer mill further grinds the dried biomass to 2.5–3.8 mm before being sent to the fast pyrolysis reactor. In the decentralized system, biomass feedstocks arrive in the form of pellets and require no need for pretreatment. Biomass feedstocks are then pyrolyzed in a circulating fluidized bed reactor at 500°C and 1 atm pressure, producing pyrolytic vapors, non-condensable gases (NCG), and solid phase products (e.g., biochar). Solid-phase materials (biochar and sand) are removed by sequential cyclones. Sand is returned to the pyrolyzer while biochar is sent to the combined heat and power (CHP) plant for energy recovery. A two-stage condenser is used to separate the bio-oil from the NCG, where part of the NCG is returned to the pyrolyzer and part is sent to the CHP. After oil recovery,
the upgrading step catalytically hydrotreats the bio-oil in an excess hydrogen environment and converts the bio-oil into hydrocarbons. The hydrogen used during upgrading is produced by the steam reforming process that uses natural gas and steam from the CHP plant. Products of upgrading contain products in two phases, that is, a gas phase, including CO₂, non-condensable hydrocarbons, and unreacted hydrogen, and a liquid phase, including an aqueous phase and hydrocarbon phase. The hydrocarbons are separated by the two-stage distillation columns, where bottom heavies are recovered and directed to a hydrocracker that cracks the heavy fraction. After hydrocracking, the resulting stream is returned to the distillation columns to produce the final gasoline- and diesel-range products. In this model, all processed off-gas, NCG, and biochar are sent to the CHP plant to recover energy. Superheated steam is produced at a pressure of 46 atm and 850°C. A portion of the steam is used in the steam turbine to generate power. Surplus electricity above the biorefinery demand is sold back to the grid.

The impacts of feedstock variations on biofuel yield, natural gas consumption, and electricity consumption and generation, were investigated through an integrated MCS and process simulation modeling framework. The ranges and statistical distributions of feedstock compositions, including carbon content, MC, and ash contents are presented in Table 1. However, it is challenging to use ASPEN Plus to run MCSs due to the large number of iterations needed (thus computationally expensive). Therefore, a surrogate model was developed in this study using artificial neural network (ANN) based on the inputs and outputs of ASPEN Plus simulations. In total, 64 samples of ASPEN Plus simulations using different combinations of biomass feedstock composition (including carbon content, MC, and ash content) (see Table S7) were obtained as the training dataset for ANN. ANN is a machine learning approach that has been used by previous studies to predict yields and product compositions of pyrolysis (Arumugasamy & Selvarajoo, 2015; Conesa et al., 2004; Hough et al., 2017; Karaci et al., 2016; Liao et al., 2019; Sun et al., 2016; Sunphorka et al., 2017). The structure of ANN model in this study consists of input layer (containing three input variables), hidden layer (containing 10 neurons), and output layer (Sunphorka et al., 2017). The ANN model was trained in MATLAB 2018a. The 64 combinations were input into ASPEN Plus simulation models, and the results of simulations were used as the outputs in the training dataset. Specifically, ASPEN Plus simulations provide mass and energy data of gasoline yield, diesel yield, natural gas consumption, and net power output. For each mass and energy result category, one ANN model will be trained. Hence, totally four ANN models were generated. The $R^2$ value of gasoline yield, diesel yield, natural gas consumption, and net power output is .98, .96, .98, and .96, respectively. To avoid the potential overfitting issues, the extra validation was conducted following the procedure in the study (Liao et al., 2019). Additional 17 runs (see Table S8) were conducted using the datasets generated by ASPEN Plus simulation models but not included in training datasets of ANN. The differences between ANN predicted results and ASPEN Plus results of four data categories were less than 1.8%, which validates the trained ANN models and eliminates the possibility of overfitting. Note that the ANN models were trained from 64 data samples, which is sufficient for this study based on the validation results. More data samples could be generated from ASPEN plus simulations, but it will be computationally intensive. Section S4 includes more details on the ANN model.

The DCFROR analysis (expressed in 2015$) was conducted in EXCEL based on design reports published by the U.S. National Renewable Energy Laboratory and Pacific Northwest National Laboratory (Dutta et al., 2015; Jones et al., 2013). The MFSP was calculated by setting the Net Present Value to 0 with an assumed internal rate of return of 10% (Humbird et al., 2011). The assumptions for the DCFROR analysis are available in Section S3 (Dutta et al., 2015; Humbird et al., 2011; Jones et al., 2013; Lan et al., 2020).

To provide more insights into real-world issues for biorefinery operations, we also evaluated the effects that biorefinery operability has on the MFSP of biofuel. Inconsistent feedstock quality (e.g., density, MC, particle distributions, and flow properties) and low efficiency with respect to handling, conveying, and storing raw biomass can have a negative impact on the overall operation of a biorefinery (Pradhan et al., 2018; Tumuluru, 2019; Tumuluru et al., 2011). For example, Kenney et al. (2013) pointed out that lignocellulosic feedstocks, which are typically cohesive, with large particle size variations and low densities, can cause bridging or ratholing issues in hoppers and on conveyors, preventing the consistent flow of biomass feedstocks. Equipment failure during handling and conveying materials can lead to a decrease in productivity or temporary shutdowns of the manufacturing line, which in turn decreases the operating efficiency of the facility and impacts its feasibility (Dai et al., 2012). According to Merrow et al. (1981), 19 out of the 43 surveyed chemical processing plants operated below 75% of their designed performance after the initial start-up period while 22 of the 43 plants did not reach 85%. One efficient solution to circumvent these challenges is to feed the biomass in a pellet form, which has a consistent quality and has a better handling efficiency than raw biomass feedstocks. For example, wood pellets can be effectively produced, handled, transported, and used at a large scale for the production of power in Europe (Ehrig & Behrendt, 2013; Nunes et al., 2014). To study this effect on biorefinery performance, the actual yield of the plant was estimated as a percentage of the design capacity, with appropriate adjustments made to the operating costs. Thus, biorefineries fed from a decentralized depot can be compared with traditional centralized biorefineries to...
understand the impacts of alternative biomass and biorefinery operations (see Section 2.4).

### 2.4 | Scenario analysis

This study compared the traditional centralized biorefinery supply system (Scenario 1) and decentralized depot HMPP supply system (Scenario 2) for several operating scenarios as listed in Table 2. In Scenario 2, three ash content levels (i.e., 1%<2%<3%) were explored for the HMPP depot at 500 ODMT/day. For both scenarios, the biorefinery capacity was 2,000 and 2,500 ODMT/day, requiring four or five depots, respectively. Four different feedstock blending ratios were selected: 100%/0%, 75%/25%, 50%/50%, and 25%/75% of the pine residues/switchgrass mix ratio (dry mass basis). To explore the impacts that the actual biorefinery performance has on the MFSP, the biorefinery was assumed to operate at 100% (ideal situation), 90%, and 80% of the designed capacity. For each case in the two scenarios, MCSs were run for 1,000 iterations to generate the results for specific uncertainties and variabilities.

### 3 | RESULTS AND DISCUSSION

As listed in Table 1, the carbon content, MC, and ash content of the pine residues and switchgrass are characterized by large variations. Such variations can be significantly reduced by depot processing. To quantify this benefit, Figures 4 and 5 show the distributions of the MC and ash content of the biomass feedstocks delivered to the biorefinery in Scenario 1 (arrived as raw materials) and Scenario 2 (arrived as pellets), respectively. As depot preprocessing only focused on MC and ash content, the carbon content distributions in the two scenarios do not show differences (see Figure S1).

In Figure 4, the blue bars display the MC distribution of the blended feedstocks (i.e., forest residues and switchgrass) for the no depot case (Scenario 1) while orange bars show the MC distribution of pellets produced by the decentralized depot in the depot case (Scenario 2). As the pellets have a uniform MC of 9% (wb), the orange bars only have one single value. Switchgrass has a significantly lower MC than the pine residues (see Table 1), therefore, increasing the blending ratio of the switchgrass lowers the MC and narrows the MC distribution. As expected in Scenario 1, decreasing the percentage of blending pine residues from 100% to 25% lowers the mean MC from 50.4% to 28.6%. From a process control perspective, however, the changes in the 5th–95th percentile (P5–P95) values range from 35.6% to 65.0% for 100% pine residues (Figure 4a) and from 20.4% to 38.5% for 25% pine residues (Figure 4d).

Figure 5 shows the ash content distributions of delivered feedstocks for the no depot (Scenario 1) and depot (Scenario 2) cases. The blending ratio has a significant impact on the feedstock ash content. For example, in Scenario 1, by decreasing pine residue blending from 100% to 25%, the ash content in P5–P95 expands from 0.5%–3.2% (mean = 1.6%) to 1.0%–6.5% (mean = 3.2%), which is due to the higher and more variable ash content of switchgrass (see Table 1). For Scenario 2, as the ash control sets a threshold for the produced pellet, and adopting the ash control can significantly narrow the range of the feedstock ash content. For example, at the 25% pine residues/75% switchgrass cases, increasing the pellet ash control level from 3% (orange bars in Figure 5l) to 1% (orange bars in Figure 5d) results in a pellet ash P5–P95 alternating from 1.0%–3.0% (mean = 2.4%) to 1.0% (mean = 1.0%), compared with the range in Scenario 1 (blue bars) of 1.0%–6.5% (mean value 3.2%). Hence, moisture and ash content controls using the depot system largely stabilize feedstock quality for the biorefinery compared with the traditional system.

To understand, in detail, the effects of using a depot with different ash control levels, Figure 6 shows the mean value of the MFSP for Scenario 1 (no depot case) and Scenario 2 (depot case) with varied blending ratios and ash control levels for biorefineries operating at 100% of their designed capacity. In Figure 6, the use of depot preprocessing (Scenario 2) results in a higher MFSP than the no depot case (Scenario 1) by $0.06–$0.43 per GGE, except for the 25%/75% pine residues/switchgrass with 1% pellet ash level case (Figure 6a). In all cases for Scenario 2, the MFSP decreases with a stricter control over the final ash content in the pellets due to a higher biofuel yield. For example, compared with a pellet with 3% ash (Figure 6c), a pellet with 1% ash (Figure 6a) reduces the MFSP by $0.10–$0.21 per GGE.

Additionally, in Figure 6, increasing the biorefinery capacity from 2,000 to 2,500 ODMT/day can reduce the
MFSP across all cases (2.7%–4.0%). In Scenario 1 (no depot case), the use of 100% pine residues shows the lowest MFSP due to a lower feedstock cost for the pine residue, as compared with the switchgrass. In Scenario 2 (depot case), the use of 25% or 50% pine residues in the pelletized feedstock yields the greatest economic benefits. The reason behind this is a trade-off between feedstock costs and drying energy. Increasing the percentage of more expensive switchgrass increases feedstock costs, but with a lower MC, as switchgrass requires less heat (from natural gas) and has a lower transportation cost due to potentially higher availability closer to the depot.

As mentioned in Section 2.3, one benefit of the decentralized depot system is the improved operability compared to the centralized system that directly uses raw biomass in the biorefinery. However, such a benefit has only been reported qualitatively in the literature (Tumuluru, 2019), and the quantitative impacts (e.g., percentage of improved operability) have not been fully understood. Therefore, this study designed conceptual scenarios to understand the system-wide...
LAN ET AL.

The depot biorefinery (Scenario 2) was assumed to be operated at 90% of its designed capacity and the centralized biorefinery (Scenario 1) was assumed to be operated at 80% for its capacity, as displayed in Figure 7. The main observation from Figure 7 is that the use of depot preprocessing and lower pellet ash content can stabilize and lower the MFSP for Scenario 2 relative to Scenario 1. Taking the 25% pine residue case (Figure 7d,h,l) as an example to illustrate how lower pellet ash content can narrow and reduce the MFSP range, the MFSP range of the 3% pellet ash level (orange bars in Figure 7l) is $0.38 ($4.49–$4.87), with a mean value of $4.73 per GGE, while the 1% ash level (orange bars in Figure 7d) shows a range of $0.13 ($4.46–$4.59), with a mean value of $4.49 per GGE. At the same time, compared with Scenario 1, the 3% pellet ash level in Scenario 2 (orange bars in Figure 7l) shows an 89% probability of reaching a lower MFSP while the 1% ash level (orange bars in Figure 7d) exhibits a 100% probability. In other words, the decentralized depot operating on pellets is more likely to reach a lower and more stable MFSP compared to traditional systems, which is consistent with the literature (Lamers et al., 2015; Pradhan et al., 2018; Tumuluru, 2019; Tumuluru et al., 2011). These examples highlight the value of this analytical approach for uncovering non-apparent interactions.

In Figure 7, comparing the centralized biorefinery (Scenario 1) to the biorefinery with a depot (Scenario 2) highlights two more conclusions: (a) increasing the switchgrass blending ratio lowers the mean MFSP; and (b) increasing the switchgrass content narrows the MFSP distribution. For example, at a 3% pellet ash control level and 100% pine residues (Figure 7i), the MCSs show that Scenario 2 (HMPP depot) has a 47% probability of a lower MFSP than Scenario 1 (no depot) while Scenario 2 has an 89% probability of a lower MFSP than Scenario 1 at a 3% pellet ash control level and 25% pine residues (Figure 7l). The reason that the 100% pine residue with 3% ash did not provide a more stable MFSP for Scenario 1 is the large dispersion in pine residue MC that produces more variable depot preprocessing costs and then less stable MFSP.

4 | CONCLUSIONS

This study conducted a coupled TEA and MCS to understand the impacts of uncertainties in biomass feedstocks and biorefinery performance on the MFSP of the biorefinery system with decentralized preprocessing sites. Scenario analysis explored the economic performance of the decentralized system with varied blending ratios of pine residues and switchgrass, biorefinery design capacities, and pellet ash control levels. The MCS results show that with depot preprocessing, variations in the feedstock moisture and ash content were significantly reduced compared to a traditional centralized system. For biorefinery operating at 100% of the design capacity, the respective mean MFSP of the decentralized system with 1%, 2%, 3% pellet ash level is $3.97–$4.22, $4.08–$4.34, $4.16–$4.39 per GGE, while the traditional system shows $3.79–$4.12 per GGE. Given the biorefinery operation inefficiencies caused by inconsistent feedstock quality, a common issue for biorefineries, this study also compares the MFSP of the decentralized system at 90% performance of the designed capacity (higher operability achieved by using pellets from depots) with the traditional system at 80% (lower operability...
due to onsite blending of two feedstocks with large quality variations). This comparison showed that, compared to the traditional centralized system, the lower and narrower MFSP distributions of the decentralized system were achieved by targeting lower pellet ash level (or say stricter pellet ash control).

This finding has an important economic implication. Based on the assumptions used in this analysis, the depot system (Scenario 2) is more efficient than the centralized system (Scenario 1) only when a higher share of switchgrass (75%) is used in the blend under the low ash content case (1%). When more ash is in the feedstock, the depot system cannot beat the centralized system without having other unmodeled benefits inherent in a uniform feedstock.

Additionally, this study also identified the benefits of blending 50%–75% switchgrass in lowering and stabilizing the MFSP. This work highlights the importance of depot concept in stabilizing feedstock quality for bio refineries, and the necessity of achieving low levels of ash and for blending switchgrass. This study also offers a chance to understand the potential effects of increasing the plant actual performance by using depot, which sheds light on future research on this topic.

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DATA AVAILABILITY STATEMENT
The data that supports the findings of this study are available in the Supporting Information of this article and from the corresponding author upon reasonable request.

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**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.