Review

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Lignocellulosic biomass feedstock transportation alternatives, logistics, equipment configurations, and modeling

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Abstract: Lignocellulosic biomass feedstock transportation bridges biomass production, transformation, and conversion into a complete bioenergy system. Transportation and associated logistics account for a major portion of the total feedstock supply cost and energy consumption, and therefore improvements in transportation can substantially improve the cost-competitiveness of the bioenergy sector as a whole. The biomass form, intended end use, supply and demand locations, and equipment and facility availability further affect the performance of the transportation system. The sustainability of the delivery system thus requires optimized logistic chains, cost-effective transportation alternatives, standardized facility design and equipment configurations, efficient regulations, and environmental impact analysis. These issues have been studied rigorously in the last decade. It is therefore prudent to comprehensively review the existing literature, which can then support systematic design of a feedstock transportation system. The paper reviews the major transportation alternatives and logistics and the implementation of those for various types of energy crops such as energy grasses, short-rotation woody coppices, and agricultural residue. It emphasizes the importance of performance-based equipment configuration, standard regulations, and rules for calculating transport cost of delivery systems. Finally, the principles, approaches, and further direction of lignocellulosic feedstock transportation modeling are reviewed and analyzed. © 2012 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: bioenergy; mechanical pre-processing and handling; performance-based standard and regulations; feedstock delivery systems

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Introduction

The emphasis on biomass-based renewable energy, including heat, power, and liquid fuels, has increased in recent years owing to the depleting fossil fuel supplies, increasing concerns regarding energy security, oil price spikes, and climate change caused by greenhouse gas (GHG) emissions from fossil fuel consumption.[1–3] Consequently, a challenging target of replacing an equivalent of 30% of current US petroleum consumption by biomass-based fuel has been set. Toward achieving that objective, it has been shown that 1.4 Gt of lignocellulosic feedstock can potentially be made available in a sustainable manner in the USA. Agricultural feedstock is expected to satisfy a major portion of the total biomass demand.[4–6]

A sustainable, reliable, and cost-effective biomass feedstock delivery system is a pre-requisite for successfully achieving the proposed targets. Such a system typically incorporates in-field harvest and collection, mechanical pre-processing, handling, on-farm storage, transportation from farms to storage facilities and from storage facilities to feedstock end-users (e.g. a biorefinery).[7–13] Thus, it is a complex combination of 'many-to-few' and 'one-to-one' collection-handling-processing-storage-delivery logistics.[14,15] Moreover, the lignocellulosic feedstock is characterized by a low dry matter density (64–224 kg m^{-3}), low energy density (10–17 MJ kg^{-1}), limited flowability, irregular forms, and high moisture in some cases, especially for agricultural residues and green grasses.[16,17] This increases the feedstock transportation cost and logistic complications. Previous studies have illustrated that the transportation costs represent between 13% and 28% of biomass production and provision costs, depending on the biomass densification level and transportation mode.[8]

A cost-competitive and reliable feedstock transportation system requires not only the optimization of delivery logistics, transport modes and pathways (or route), but also the configuration of processing, handling, and transportation equipment and facilities in terms of biorefinery plant size and conversion technology.[18] The design and operation of the transportation system significantly depends on the intended use of biomass, feedstock type and productivity, geographical location, and natural resource availability. These issues have been discussed in the literature, but often independently. Therefore, it becomes necessary to comprehensively review the existing literature on these topics, so as to conduct a systematic analysis and innovative design of a feedstock transportation system. This is the goal of this review. Additionally, the review draws conclusions and provides recommendations based on the literature.

Potential biomass transportation modes

The transportation options of lignocellulosic feedstock include roads, railways, waterways, pipelines, and/or a combination of two or multiple options.[14,18,19] The most likely means of biomass transportation is by road using in-field bale-mover tractor, haulage wagon, tractor-trailer combinations, truck-tractor-semi-trailer combinations, or a container lorry, especially for small- and medium-scale transportation requirements. Road transport is generally applied for relatively short distances (<100 km) when flexibility is required and multiple (small) farm sites have to be accessed, or when rail and waterway infrastructure is absent.[8,9,20,21] For instance, about 80% of pulpwood delivered to US mills in 1996 arrived by truck.[22–24] In Austria, where typical road transportation of biomass for heating and combined heat and power (CHP) ranges from 20 to 120 km, tractor trailers are commonly used for short distance transport (about 10 km) of unchopped thinning residues, forest wood chips, and various herbaceous feedstock.[18] Although road transportation has low fixed costs, it has higher variable costs such as fuel consumption, labor, tires, and wear costs. For example, in the USA, the delivery cost of switchgrass was 14.68 \$ Mg^{-1} (USD in 2000) including average truck cost of 8.44 \$ Mg^{-1} and loader cost of \$2.98 Mg^{-1}.[10,24] The energy consumption of road transport over a distance of 100 km accounts for roughly 10% of the biomass inherent energy content.[9,10] One must also consider the infrastructure limitations, traffic congestion, and environmental impact resulting in indirect costs. More than 15 truck deliveries per hour are required for a biorefinery consuming 1–2 Tg of dry corn stover per year causing traffic congestions.[4,20,21] As the biorefinery size increases, a larger collection area and longer transport distances are necessary to ensure year-round supply, which exacerbates these problems. Moreover, dedicated and long-term storage facilities will be necessary since a biorefinery may typically store only up to 7–10 days of biomass feedstock supply.[25] Therefore, an assumption of single biomass transportation mode could be overly simplistic and not really optimum.

Rail transportation usually requires a large fixed investment to develop infrastructure and offers lower flexibility. However, it becomes cost-effective for medium to long overland transport distances (>100 km) involving stable and constant flow of goods. This is owing to its low variable cost, especially for logs, bales, bundles and industrial densified biomass (e.g. pellet, briquette, bagged powder, wood saw, or sorghum chip modules).[26] For example, in Alberta, Canada, the distance variable cost for rail transport of straw and wood chips was 0.0277 and 0.0306 \$ dry Mg^{-1} km^{-1}(USD in 2004), respectively. These were significantly lower than 0.1309 and 0.1114 \$ dry Mg^{-1} km^{-1} (USD in 2004) for road transportation.[24] The fixed costs for rail transport, however, were 17.01 and 9.97 \$ dry Mg^{-1} km^{-1} (USD in 2004), respectively, which were significantly higher than 4.76 and 4.98 \$ dry Mg^{-1} km^{-1} (USD in 2004) for road transport. The railcar equipment cost is a function of biomass type, form, quantity and distance to be transported.[21,24] The cost benefits of rail transport for long-distance and large-scale feedstock delivery also depend on the availability of return freights, transfer terminal policies and route infrastructure.[24]

Waterborne transportation is applied for long distances, especially in international transport. It has a cost structure similar to rail transportation, requiring high capital investment in ships and freighters, but incurring low variable costs and low energy use per Mg-km.[17] It is especially relevant for the transportation of pellets or briquettes, which are becoming an internationally traded feedstock form. In Scandinavia, for instance, the transport of pellets by water, within Scandinavia as well as from Canada, has become greatly relevant for combustion and co-firing.[23,24] In Europe, long-distance transport of pellets costs between 0.020–0.022 € dry Mg^{-1} km^{-1} (euro in 2003) (0.021–0.023 \$, USD in 2003) by train and only between 0.001–0.012 € dry Mg^{-1} km^{-1} (euro in 2003) (0.001–0.0126 \$, USD in 2003) by ship.[18] In addition to pellets, woodchips and bales (or bundles) can also be transported by ship. Inland use of this mode of transport though is limited by the availability of waterways such as rivers and lakes.

Pipeline transportation offers another alternative to deliver the low energy density biomass feedstock to a large scale bioenergy plant.[21,22] Although pipeline transportation is associated with high capital investment and low per-unit operating costs, the large demand and supply rates for lignocellulosic feedstock may justify the development of a pipeline network. It has been shown that by using a slurry of wood chips, pipelines would be economical in comparison to delivery by trucks only at large capacity (greater than 0.5 million dry tons per year for a one-way pipeline, and 1.25 million dry tons per year for a two-way pipeline that returns the carrier fluid to the pipeline inlet), and at medium to long distances (greater than 75 km for one-way and 470 km for two-way at a capacity of 2 million dry tons per year). For corn stover at 20% of solids concentration or higher, pipeline transport is more economical than truck transport at capacities greater than 1.4 million dry tons per year when compared to a mid-range of truck transport costs. In addition to taking advantage of the economy of scale of the plant, transportation using pipeline also offers the opportunity to implement innovative logistics such as simultaneous transportation and saccharification of biomass.[22,23] The challenges include maintaining the feedstock quality and stability as it mixes with the carrier fluid, and providing a large amount of water resource. Maintaining pipeline temperatures and prevent them from freezing will also be critical and may restrict their use to limited regions.

Intermodal transportation combining multiple transportation types may be a solution for a large-scale biorefinery. Here, two or more modes of transportation are combined without changing the containment, and may require the development of facility or infrastructure such as distribution centers (e.g. centralized storage or depot facilities).[4,18,19,20,22,23] One likely example is the combination of road transport with rail or waterway transport, as done in Australia for transporting sugarcane to the mills.[20,25] Trucks or trailors can be used for on-farm collection, short distance hauling to a local storage, processing or depot facility alongside a rail track or waterways. The feedstock can then be loaded onto rail cars or ships (after possible short-term storage) and transported directly to the mill. The final leg of transportation for local distribution can again be carried out by road. Thus, intermodal transportation typically takes advantage of the low variable costs for rail or waterborne transportation and high flexibility of road transportation.[4] The mills can have dedicated railway tracks or waterways to ensure that the feedstock supply is reliable and meets the biorefinery demands. A similar arrangement using pipeline transportation can also be envisioned.[22] The coordination of intermodal transportation is normally more complex than that of unimodal transportation, because it requires more handling (trans-loading) of feedstock as well as interactions among several stakeholders.[26]

In summary, an appropriate feedstock transportation mode depends on the intended biomass use, biorefinery plant capacity, facility and infrastructure, biomass form and quality variables, and environmental impacts. A performance-based evaluation and analysis of alternative modes that incorporates these attributes within the transportation logistics framework along with equipment configurations is therefore required.

Lignocellulosic biomass feedstock delivery logistics

Lignocellulosic feedstock delivery logistics depend significantly on the feedstock type.[26] Delivery logistics of major feedstock types such as dry energy grasses, green energy crops, short-rotation woody biomass and agricultural residues are thus synthesized as follows (Fig. 1).

Dry energy grasses

As a major lignocellulosic feedstock source, the common annual and perennial dry energy grasses include Miscanthus (*Miscanthus* × *giganteus*), switchgrass (*Panicum virgatum*),

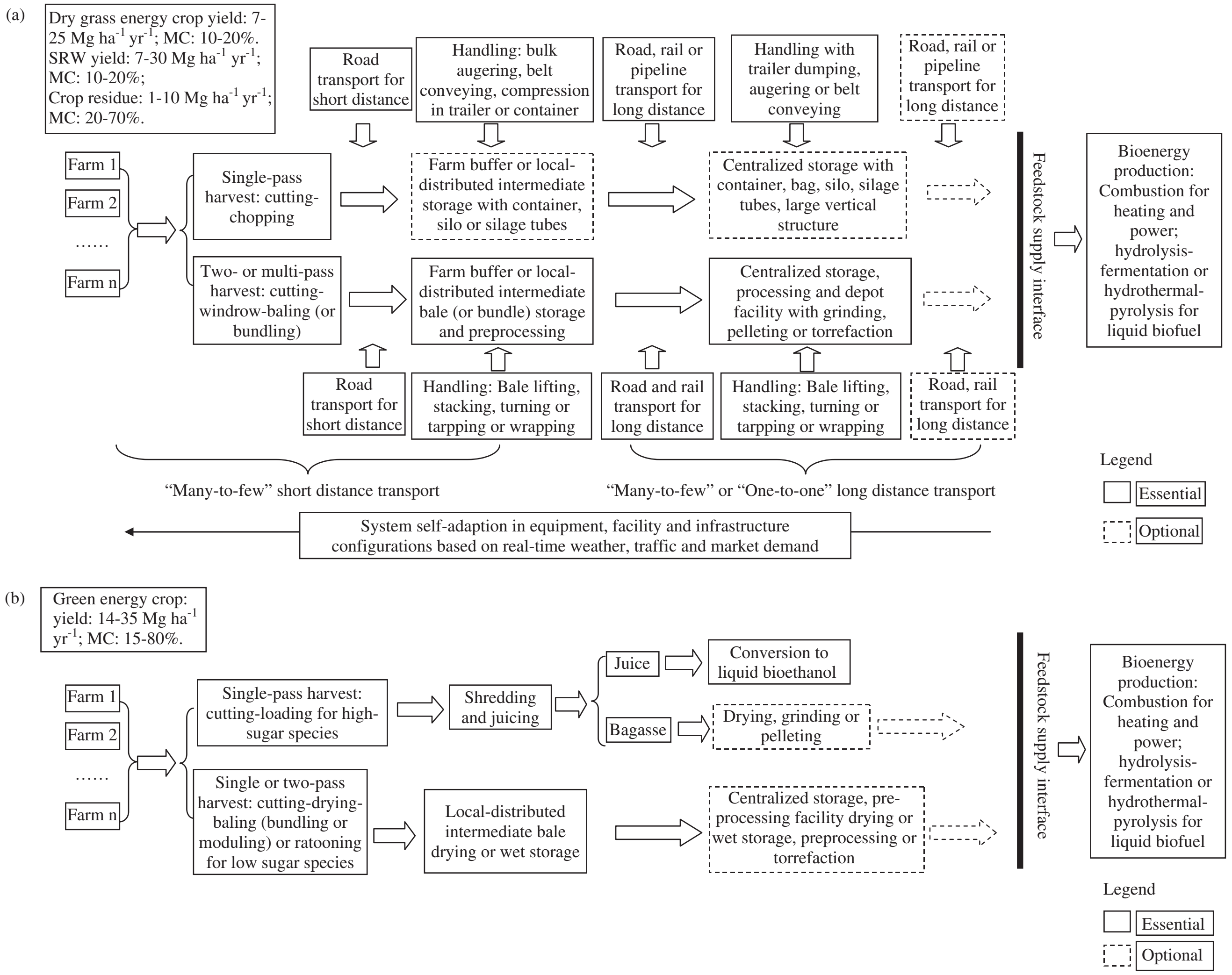

Figure 1. Schematic chart of lignocellulosic feedstock delivery logistics of (a) dry grass energy crops, short rotation woody coppice, crop residues and (b) green energy crops. Feedstock drying or wet storage and preprocessing are the major differences in supply logistics between dry and green energy crops. Note: MC – moisture content (%).

prairie cordgrass (*Spartina pectinata*), reed canary grass (*Phalaris arundinacea* L.), elephant grass (*Pennisetum purpureum* Schumach.), big bluestem (*Andropogon gerardii*), and eastern gamagrass (*Tripsacum dactyloides*). Dry energy grass feedstock is characterized by high biomass yield, seasonal availability, low moisture content, low packing bulk density, and significant biomass loss during harvesting, processing and delivery. The average dry matter yield of *Miscanthus* × *giganteus* ranges from 7 to 25 Mg ha^{-1} yr^{-1}.[27,29] The harvest-to-delivery logistics of dry herbaceous energy crops require large equipment for harvest, preprocessing and handling, high volumetric capacity of transportation vehicles, and large storage facilities. Low moisture of the dry grass feedstock makes storage relatively easy. For instance, the moisture content of Miscanthus and switchgrass ranges from 10 to 20% when harvesting in late fall and early spring, respectively, at the Energy Farm of the University of Illinois at Urbana-Champaign. Through in-field windrowing, the moisture content of Miscanthus and switchgrass reached as low as 10–15%, the baling moisture level.[29] Dry grass feedstock could then be stored in bales or in bulk form at intermediate facilities such as open air shield, on-farm buffer (with or without tarp or wrapping), silage pits, bunkers, or existing farm buildings.[9,30–36] The seasonal availability and yield uncertainty caused by weather may increase the cost of obtaining these resources, while leading to suboptimal utilization of the harvesting and on-farm handling equipment, workforce as well as storage space.[20,25]

Mechanical densification, size reduction, and torrefaction take a crucial role in converting grass biomass from highly variable resources into a reliable commodity for bio-based industries. However, mechanical comminution and compression of dry grasses often represents a major portion of the supply costs, with some estimates placing it at 20 to 40% of the total biomass-to-biofuel cost.[36] With commercial-scale hammer mills, for instance, energy consumption for grinding switchgrass through 0.8 mm and hardwood through 1.6 mm mill screens are between 1–3% of their inherent heating value.[16,17] The location and time of size reduction, densification and/or torrefaction also influences the efficiency of the whole supply logistics. There is an argument to place size reduction, densification, and torrefactions before transportation and to uniformly handle and transport flowable feedstock to end-users with standard equipment and management procedure.[36] We recommend a hybrid delivery scenario combining the advantages of baling at the farm-gate followed by intermediate pre-processing to a standardized uniform particle supply, where the uniformity refers to the physical and chemical properties of the feedstock.[29] In this scenario, bales are transported from a farm to a centralized facility for storage and comminution. Here, a horizontal or tub grinder (chopper or shredder) and large-scale grinding facility (e.g. pilot demonstration unit (PDU) developed by Idaho National Lab of the US Department of Energy) is used to produce fine particles based on the demands of the biorefinery. The uniform particles are transported immediately to the biorefinery at a constant supply rate with standard handling and transport equipment and procedure.[29]

The bioenergy plant capacity significantly affects the logistics and efficiency of dry grass feedstock delivery. For a small Miscanthus-burning power plant with less than 20 km transport distance, the total transportation cost of 3-cm Miscanthus chips was 35% of that of bales and much lower than that of pellets.[35] Bales or pellets (briquettes or cubes) are widely considered as an efficient form for a medium or large combustion-power plant. For a large-scale bioenergy plant, multiple storage (e.g. storage and processing depots) units and intermodal transportation can be employed. The optimization of satellite storage locations or centralized storage and processing facility becomes important for a local-distributed depot processing-delivery system.[7,35]

Short-rotation woody (SRW) feedstocks

In North America, the SRW energy crops mainly include black willow (*Salix nigra* M.), hybrid poplar (*Populus hybrids*), cottonwood (*Populus deltoides*), American sycamore (*Platanus occidentalis* L.), slash pine (*Pinus elliottii*), loblolly pine (*Pinus taeda* L.), sweetgum (*Liquidambar styraciflua* L.), leucaena (*Leucaena leucocephala* (Lam.)), and castor bean (*Rininus communis*).[28,39] SRW plantations are featured with high moisture content, high yield, multiple-stem plantations, and spatial harvest rotations of tree shoots over 2–5 years for at least 30 years. For example, average UK commercial willow feedstock yield is 7–18 Mg DM ha^{-1} yr^{-1},[28] which are within the yield range of spring harvested

Miscanthus × *giganteus* of 7–25 Mg DM ha^{-1} yr^{-1}. The moisture content of winter-harvested willow generally is in the range of 40–55% at harvest. Thus, drying of SRW feedstock from about 40–50% (dry basis) to less than 15% (dry basis) is challenging.

The SRW harvest-to-delivery logistics and equipment requirement is usually composed either of single-pass cutting (or slashing)-bundling, cutting-baling or cutting-chipping, or two-pass cutting-baling or cutting-bundling systems. In North America, cutting (or slashing)-baling or cutting-chipping systems are more popular for SRW coppice, while cutting-bundling harvest equipment is widely used in Europe. The SRW harvest-to-delivery can use the equipment for harvesting and transporting understory forest biomass feedstock. A comparative study of the single-pass Biobaler and a two-pass Fecon mulcher cutting head combined with a Claas baling system showed that by using the single-pass Biobaler system, biomass loss (57%) is 9% higher than that of the two-pass Fecon mulcher/Claas baler system (48%). However, the cost of the Biobaler system per unit area (320.91 \$ ha^{-1}) was lower than that of the mulcher/Claas baler two-pass system (336.62–596.77 \$ ha^{-1}).[39] The cutting, baling and handling systems for SRW coppice usually consume more energy than that for the energy grasses.[39] For example, for baling SRW crops, the Biobaler MT565B and WB55 required a minimum PTO power of 108–135 kW, which is higher than the 75–90 kW of the New Holland 9000 series balers for grass energy crops.[39] SRW bales and chips are suitable to be transported by road for short-distances. In some cases, the SRW coppices are also densified to pellets on farm or at satellite and centralized pellet mills. Pellets from SRW coppices can be transported over long-distances for regional or international trade by rail or ship.

Green energy crops

Green energy crops mainly include different varieties of sorghum and energy cane. High moisture content, high yield, and the associated quality issues often lead to collection and logistics that are different from those for the dry energy grasses.

The sorghum varieties include grain sorghum, forage sorghum, sweet sorghum, and photoperiod-sensitive sorghum.[40] The average yield of energy sorghum is between 14–35 Mg DM ha^{-1}. The harvesting and transportation logistics of forage sorghum are expected to be similar to those for dry grass energy crops. If sorghum moisture is in the baling range, forage chopping is a convenient mean of harvest. The harvested sweet sorghum must be shredded and juiced within 16–48 h due to high sugar fraction. The logistics and equipment of shredding (or chopping) and extracting sugar from sugarcane could be a paradigm for sweet sorghum. For some regions, energy sorghum management practices (e.g. ratooning) included multiple harvests in a single season and 'just-in-time' harvest systems, thereby requiring minimal storage.[39] With proper management practices, sorghum moisture can reduce to the 15–20% range required for baling.[41]

The harvest and transportation operations of energy cane are governed by the composition of the energy cane. Varieties with high sugar content need to be processes quickly, while those with high fiber and low sugar contents can be processed and handled similar to grass or woody biomass. The current harvesting, handling, and pre-processing technologies and equipment for energy cane are similar to those for sugarcane due to the similar physical characteristics.[42] The energy cane systems comprise soldier harvesters or combines that chop the cane into billets. Preliminary studies have shown that the total transportation cost for energy cane is in the range of 4–5 \$ Mg^{-1}, which is about 14% of the total production cost.[42] The storage and comminution of energy cane billet and bagasse are challenging because of its high moisture, low storability and grindability. Similar to sweet sorghum, harvest management and ratooning of energy cane can reduce the storage requirements.

Agricultural residues

Agricultural residues mainly include arable crop residues, and stalk and branch residues from orchard and horticultural plants. Hereinafter, we mainly discuss crop residue delivery logistics.

Crop residues including crop straw or stover, cotton- and sunflower-stalk, are characterized by seasonal availability, low bulk density, and uncertain moisture content. Biomass yields of crop residues range from 1–10 Mg DM ha^{-1} yr^{-1}, which is significantly lower than that of energy crops.[43–46] The moisture content of corn stover, soybean stems and leaves, rice straw and sunflower stalk varies between 30% and 70%, while the moisture contents of wheat, oat and barley straw range from 10% to 20%. Natural windrowing or artificial drying is the critical step for some green residues, for example, early harvest crop residues.[44]

The collection and delivery of crop residues have often been integrated with harvest and processing of the primary products (e.g. grain, oil seed, or fruit). There are two types of harvest-to-delivery systems commonly used for crop residues: (i) delivery of the whole crop (e.g. single-pass one- or two-stream systems) including feedstock and grain harvest altogether, and (ii) delivery of the primary product (grain or fruit) and agriculture residues separately (by-product) (e.g. conventional two-pass harvesting system).[43,44] One-pass systems are usually regarded as an efficient way to decrease biomass loss and collect more feedstock than that of the conventional two-pass systems. The residue obtained from the two-pass system may be contaminated with soil in the process of in-field windrowing.[47–49] By setting the combine mower header at ground level, the one-pass combine machine collected approximately 2.5 Mg ha^{-1} more wheat-straw than swathing and baling following windrowing.[47–49] Richey *et al.* reported that the collection of corn stover by baling or stacking following windrowing recovered only about 50% of the windrowed material.[48]

The harvest-to-delivery technology and equipment for crop residues are more complicated and more seasonal than those for forage and energy grass because the crop harvest, processing, and delivery operations have to manage the grain as well as the residues. For the single-pass harvester, the two-stream harvest combine is more popular for grain crops, while the one-stream equipment is often adapted for prairie grass. The capacities of the in-field bale pick-up, haulage trailer and the intermediate storage facility of crop residues are smaller than those for the energy crops. Similar to grass energy crops, bulk densities of large bales and modules of corn stover are only 200 and 110 kg DM m^{-3}, respectively, and densification of crop residues is required to reduce the transportation and storage costs. Local delivery from field to an intermediate storage facility takes an important role because of the lower feedstock yield of crop residues, and is mainly by road transport with a tractor-wagon or truck-trailer.[49]

Performance-based standardizations and configurations of feedstock preprocessing, handling and transport equipment, and regulations

Non-standardized and diversified equipment, vehicles, and management procedures create barriers to simplify feedstock delivery logistics and streamline supply management.[50–52] Presently, there is a lack of specialized equipment, facility, and management regulations for harvesting, preprocessing, handling, transporting, and storing dedicated energy crops. The majority of existing equipment, facility, management procedures and regulations used for energy crops were designed for agricultural crop, forage, or forest residues rather than dedicated energy crops. For instance, 14.6-m trailers are commonly used to deliver forage bale, but 15.8-m and 16.2-m trailers or truck beds are also employed in the USA. For a self-loading-self-unloading bale-hauling truck, a hydraulic bale pick-up arm can place about 36–40 bales on the bed, but a 15.8-m flatbed truck can only haul about 25 bales with a bale size of 0.9 × 1.2 × 2.1 m. Walking floor trucks are able to transport 10,000 kg (~100 m^3) of Miscanthus chips.[50–52] Therefore, performance-based evaluation and standardization of the transport vehicles, handling and processing equipment, storage facilities, and management procedures are needed to improve delivery efficiency and enforce regulations and policies of feedstock transportation.[8] Specialized delivery equipment and facilities should be developed for dedicated energy crops.

The standardization of transport equipment and management regulations has to consider the biomass form, properties, and biofuel conversion technology.[7] Hess *et al.* reported that the standardized uniform or advanced uniform supply logistic and equipment can increase efficiencies by comminuting biomass feedstock to small sizes and improving bulk-handling efficiency and bulk density.[36] Miao *et al.* suggested that the volumetric flow efficiencies of Miscanthus and switchgrass particles ground through a 12.7-mm screen by tub grinder are 2.0 and 2.8 times higher than the counterparts of the particles through the 25.4-mm screen, respectively.[29] However, biomass form and properties such as size, weight, and bulk density vary with farm and species. For instance, among the 1.1 × 0.8 × 1.1-m, 1.2 × 1.2×2.4-m or 0.9 × 0.9 × 2.1-m rectangular

Miscanthus and switchgrass bales, the weights range from 570 to 720 kg DM and from 280 to 350 kg DM, respectively.[29] Bulk densities of corn stover and switchgrass pellets and briquettes range from about 352 to 609 kg m^{-3}.[29] Standardization of end-users' feedstock demand and biorefinery technology is a prerequisite to standardize feedstock preprocessing and handling equipment, delivery vehicles, and storage facilities.

Standard delivery vehicles should be multipurpose and infrastructure compatible, and be able to transport not only high weight load, but also high volume load. The specialized vehicles and facilities must remain within certain parameters such as axle mass limits and comply with local traffic laws and regulations.[36,53–55] In South Africa, for instance, a fleet of vehicles for sugarcane transport must comply with a set of regulations, which specify limits on length, power-to-weight-ratio, axle loadings, and gross mass.[53–55] According to US road traffic rules for bale trailers, the steering axle weight should not exceed 5440 kg and the second and third axle weights should not exceed 15 400 kg per axle. The total weight of truck and biomass should not exceed 36 000 kg. Fixed trucks, which are less than 12.2-m in length, allow more maneuverability in traffic-tight areas.[55] These factors must be considered while designing the performance-standardized equipment.

Biomass feedstock transportation logistic modeling

The complexity and interdependency of challenges highlighted in the preceding sections motivate the use of system-level mathematical modeling approaches for simulating and optimizing biomass transportation logistics. These models usually include biomass production, feedstock transformation, and supply and demand components, which are viewed from economic, environmental, and even social perspectives.[56] In the past, two major types of models have been developed for feedstock delivery: optimization models, and event- (or process) based simulation models.[56] In recent times, heuristic, agent-based, and artificial intelligent self-learning and self-adaptive models have also gained popularity and acceptance. These are briefly described below:

Mathematical programming

De Mol *et al.*[57] proposed an MILP (mixed integer linear programming) model using a network map (nodes and links) to analyze storage and transportation options. Shastri *et al.*[34,35,58] developed a system-level MILP model called BioFeed that optimizes annual transportation fleet sizing and scheduling. Other MILP model applications in feedstock industry include Mapemba *et al.*,[56,59] Milan *et al.*,[60] Grunow *et al.*,[61] and Cundiff *et al.*[62]

Discrete-event simulation and system dynamics

The IBSAL (Integrated Biomass Supply and Logistics) model adopted the DES approach to simulate biomass feedstock supply chains.[9,10] Iannoni and Morabito[63] applied the DES approach to sugarcane logistics from farms to the mill. Mukunda *et al.*[44] applied DES to corn-stover logistics for a biorefinery, while Ravula *et al.*[11,12,64] used DES to compare various policy strategies for scheduling trucks in cotton-gin logistics systems and biomass transportation for ethanol production. Similar to discrete event simulation, the system dynamic approach has been used to investigate the impacts of biomass feedstock price, transportation costs, and government regulations/incentives on the growth of the US corn ethanol industry.[65]

Queuing theory

Applications of queuing theory for a vehicle routing problem can be found in Van Woensel *et al.*,[66] Vandaele *et al.*,[67] Jain and MacGregor Smith,[68] and Kang *et al.*[69]

Heuristic and agent-based models

A multi-objective heuristic approach has been employed to optimize forest biomass supply chains.[70–72] Ramstedt[15] developed a multi-agent-based simulator (TAPAS) to explore the influence of transport policies on decision-making in transport chains. The Argonne National Laboratory of the US Department of Energy developed an agent-based model to analyze alternative combinations of energy production and delivery systems and determine the best transportation in terms of cost, safety, and energy efficiency. Scheffran and BenDor developed a spatial-agent dynamic model to investigate the influence of decision rules, demands, prices, subsides, carbon credits, the location of ethanol plants and transportation patterns on energy crop production in Illinois (USA).[73]

Artificial Neural Networks

Celik[74] used the supervised learning method of neural networks to simulate freight distribution. NREL (US National

Renewable Energy Laboratory) DENNIS^{TM} (Distributed Energy Neural Network Integration System) simulated energy spatial interactive delivery systems.[75]

Among these modeling approaches, the mathematic programming, heuristic, agent-based, and neural network model are more applicable to strategic planning and management analysis. Queuing theory, discrete event simulation and system dynamic could be used to develop event- or process-based model at feedstock delivery tactical and operational levels by combining with real-time geo-referenced information and technology. The operational level models should preferably include spatially explicit real time weather and traffic conditions, route optimization, fleet tracking, and facility and infrastructure configurations. These models should also be calibrated and validated using a real system, which is often challenging. It is also important to ensure uniformity in the evaluation criteria across multiple models. This is especially true for non-economic performance measures such as energy consumption. Here, we recommend the use of percentage of inherent heating value (PIHV) to quantify energy consumption and compare alternatives. The PIHV of an operation gives the percentage of the inherent heating value of the biomass that is used up for that operation.[29,55] For economic analysis, currency purchase power parity rather than simple US dollar or euro currencies should be adopted as the rules of thumb.

Conclusion and recommendations

Transportation is a crucial component of the biomass production system. Different modes of transportation, including roads, railways, waterways, pipelines, and combinations of these, have been extensively studied in the literature. Currently, road transport is the most preferred alternative, primarily due to the high flexibility offered at relatively short collection distances. As transportation distance and feedstock demands grow, intermodal transportation incorporating rail, waterways or pipeline will need to be considered. However, the design of a cost-effective and reliable transportation system goes beyond simple mode selection and includes the consideration of farm, storage, and biorefinery sites, transportation mode availability, equipment and facility configurations, regulation, policy and environmental impact analysis. These issues must be considered in combination with biorefinery capacity, feedstock type and form, intended use, storage and pretreatment technology, handling and processing equipment, infrastructure specifications, and geo-spatial features. The optimal selection should be aided by performance-based standardization of feedstock forms, delivery equipment, facility and regulations. There is an argument to place mechanical (and torrefaction) pre-processing before transportation and storage, and incorporate storage with pretreatment to unify the lignocellulosic feedstock transportations.

Transportation logistics and equipment configuration are substantially dependent upon feedstock features. For prairie grass energy crops and agricultural residues, densification (including torrefaction), and size reduction are crucial logistical steps to improve feedstock delivery efficiency. For short-rotation woody biomass and green biomass stock, natural or forced drying may be necessary to control biomass degradation during transportation and storage. The review identified that there is a lack of literature on performance-based evaluation and design of feedstock supply procedures, equipment, facility, transportation regulation and policy. An integrated framework that addresses these challenges will be useful to develop a biomass transportation model and management system at an operational level. To standardize the feedstock delivery systems, the efficiency modeling of feedstock delivery systems should be based on the currency purchase power parity or the ratio of energy consumption of the systems to inherent heating value of the feedstock.

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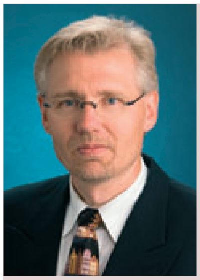

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