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Biomass logistics: A review of important features, optimization modeling and the new trends

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A B S T R A C T

Biomass logistics comprise of inter-dependent operations related to harvesting and collection, storage, pre-processing, and transportation. Its high cost represents one of the barriers in widespread use of biomass for energy and fuel production. Therefore, improving and optimizing biomass logistics are essential in overcoming this barrier. Biomass logistics was reviewed in a previous study that aimed at categorizing logistics operations, but the inherent issues and complexities, and how they were incorporated in mathematical models were not discussed in detail. The objective of this paper is to review the important features of biomass logistics operations, discuss how they were incorporated in mathematical optimization models, and explain the new trends in biomass logistics optimization. Differences between the models dealing with forest-based and agriculture-based biomass are highlighted. Important features incorporated in logistics models include demand-driven and supply-driven collection, collection of biomass in different forms, storage at intermediate facilities, biomass quality deterioration, inter-modal distribution for long-distance transportation, operational level transportation planning, and planning the pre-processing of biomass. Recent trends in biomass logistics models include the consideration of scattered availability of biomass across supply areas, uncertainties in biomass supply, integration with GIS, emissions from logistics operations, and traffic congestion due to biomass transportation. Most of the literature on biomass logistics focused on medium-term planning, while that for short-term planning is still in its infancy. The current biomass logistics models focused mainly on economic objectives, while environmental concerns related to emissions from logistics activities received limited attention. The trade-off between environmental and economic aspects of biomass logistics operations have not been investigated. Social aspects such as increase in traffic congestion due to biomass transportation received limited attention in the literature. Most of the previous models were tested on hypothetical cases, while developing suitable models to address practical issues in real case studies would be valuable.

1. Introduction

Biomass is a clean and renewable source of energy that has gained importance in the recent past. It can be used to generate heat, electricity, biofuels or a combination of them [1]. Biomass can also be stored and be used on-demand [2]. Because of its local availability, biomass can increase fuel security and reduce carbon dioxide emissions [3]. Due to numerous advantages of using biomass, significant effort has been made in developing advanced technologies to convert it to energy and fuels.

Although improvements in conversion technologies and processes are key in advancing the use of biomass, logistics is realized to be an important aspect in planning bioenergy/fuel production systems [4]. Biomass logistics decisions are generally made during medium and short term planning levels [5]. They involve operations in the upstream of the supply chain related to harvesting and collection, storage, pre-processing, and transportation of biomass [6] as well as in the downstream of the supply chain related to storage, transportation, and distribution of bioenergy and biofuels. Fig. 1 shows the biomass supply chain network and the logistics decisions at each stage of the supply chain.

Logistics cost is a major component of bioenergy and biofuel costs [2], and in some cases it represents as much as 90% of the total feedstock cost [7]. As a result, improvements in logistics could play a key

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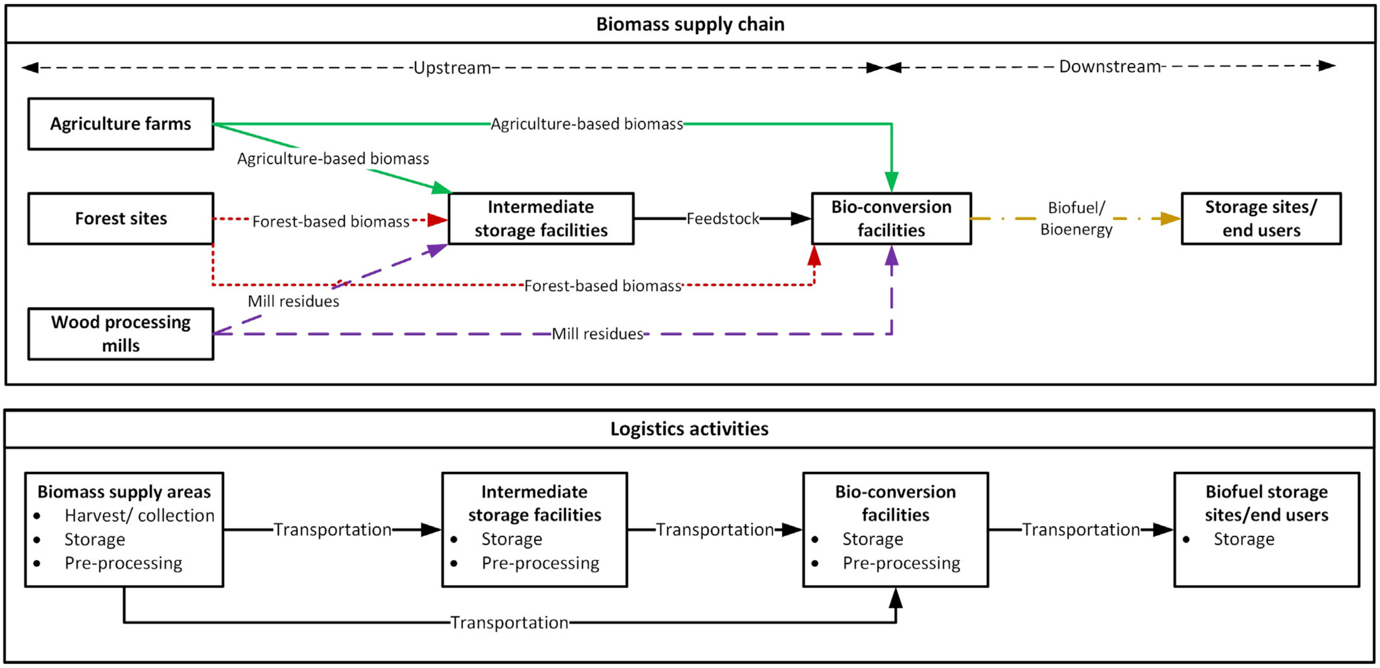

Fig. 1. Biomass supply chain and logistics activities.

role in biomass utilization [8]. Due to its significance, numerous optimization models have been developed in the literature to minimize the total logistics cost.

Optimization of biomass logistics is complex due to the characteristics of biomass such as its seasonal availability, scattered geographical distribution, and quality variations, as well as inter-dependencies among logistics operations [9]. Incorporating all these features in optimization models makes them very large and difficult to solve. Moreover, due to the differences in crop rotation cycles, logistics networks, and biomass collection methods, models for agriculture-based biomass and forest-based biomass logistics planning differ significantly. Therefore, different models are required for different types of biomass.

Several review articles have been published on biomass supply chain and/or logistics optimization. A group of them focused only on forest-based biomass (e.g., [10,11]), while another group focused on agriculture-based biomass (e.g., [12,13]). Few recent articles reviewed the mathematical aspects of optimization models such as the objective function, decision variables, and the solution method used to solve the models (e.g., [4,14]). However, description of biomass logistics operations, related complexities, and modeling techniques have been confined only to brief explanation in previous reviews. To the best of our knowledge, the only review on biomass logistics was generic with a focus on categorizing biomass logistics operations [8]. While the key aspects of biomass logistics were described in [8] by reviewing 54 articles published between 2000 and 2009, modeling aspects and key findings from the literature were not discussed. Moreover, new trends in biomass logistics models such as the consideration of uncertainties in biomass supply, environmental and social concerns, and multi-modal transportation of biomass, which are mostly developed in recent literature, were not covered in previous reviews.

The aim of this paper is to provide a review of key features of biomass logistics operations, how they were incorporated in mathematical optimization models, and the new trends in biomass logistics optimization. Similar to Gold and Seuring [8], biomass logistics operations are categorized into (1) harvesting and collection, (2) storage, (3) transportation, and (4) pre-processing of biomass. First, previous reviews and how this review differs from them are explained in Section 2. Next, the decisions, key features and complexities in each logistics operation, and how they were incorporated in mathematical models are described (Section 3). Then, the new trends in biomass logistics optimization models are reviewed (Section 4). Finally, main findings, gaps and potential future directions for research are discussed. While the number of papers dealing with logistics-related decisions in biomass supply chains is large, this study focuses on the papers that would be useful in describing the key features, complexities, mathematical modeling approaches, and new trends in biomass logistics, not all the studies related to this topic.

2. Previous reviews on biomass supply chain and logistics optimization

Biomass supply chain optimization models have been reviewed in several previous studies. A group of them focused solely on forest-based biomass supply chain. Shabani et al. [15] reviewed deterministic and stochastic optimization models for utilizing forest-based biomass in district heating plants, power plants, biofuel plants and co-generation plants. Strategic (long-term) and tactical (medium-term) optimization models that addressed sustainability aspects using multiple objectives (economic, social and environmental) for forest-based biomass supply chains were reviewed by Cambero and Sowlati [10]. In a review by Sowlati [16], key characteristics of forest-based biomass supply chains such as the complexities, decision planning levels and supply chain issues were discussed. Several single objective, multi-objective, stochastic programming, robust optimization, simulation, and hybrid simulation and optimization models were also reviewed. More recently, Malladi and Sowlati [11] reviewed operational level (short-term) transportation optimization models in forestry and included a section on forest-based biomass transportation.

An et al. [12] and Yue et al. [13] provided reviews of studies focusing mainly on the production of biofuels. The review by An et al. [12] discussed few simulation and optimization models related to strategic, tactical and operational level planning with the aim of comparing biofuel and petroleum-based fuel supply chains. Yue et al. [13] focused more on the supply chain aspects of biofuel production such as integrated decision making, competition among different players of the supply chain, and centralized/decentralized decision making. The focus of these two reviews was more on agriculture-based biomass than on forest-based biomass.

Few review articles considered some general aspects of biomass supply chain management. A detailed review of 32 articles was provided by Sharma et al. [17], who discussed aspects related to decision levels, supply chain structure, modeling approach, quantitative performance measure, products involved in the supply chain, novelty, application and assumptions, limitations and gaps specific to the selected papers. Mafakheri and Nasiri [18] reviewed six policy issues, namely technical, financial, social, environmental, policy and regulatory, and institutional and organizational issues, which influence the design and planning of biomass supply chain operations.

A group of review articles focused on mathematical modeling and solution approaches used for biomass supply chain optimization. De Meyer et al. [19] classified the studies on optimization models according to the solution method adopted to solve them. Specifically, studies were classified into those dealing with mathematical programming models, heuristics, and multi criteria decision analysis. Biomass supply chain models were categorized into deterministic, stochastic and multi-objective optimization models by Ba et al. [4]. The focus of their review was on mathematical aspects such as the solver used, number of variables and constraints in each model. In a more recent review, Atashbar et al. [14] categorized studies into those dealing with strategic, and tactical and operational level plans, and each of the categories were sub-classified into single objective and multi-objective models. Similar to Ba et al. [4], their focus was on the modeling aspects such as the objective function, decision variables and the optimization method used to solve the models.

While logistics operations and associated decisions have been discussed in the previous review articles, they were limited to brief descriptions without explaining the inherent complexities and how they were incorporated into mathematical models. To the best of our knowledge, the only review article which focused solely on biomass logistics was by Gold and Seuring [8], who reviewed 54 papers published between 2000 and 2009. However, according to other studies such as [4], the review by Gold and Seuring [8] was general which aimed at classifying the literature based on biomass supply chain management and logistics issues for bio-energy production. Logistics decisions were categorized into harvesting and collection, storage, transportation, pre-treatment of biomass,

3. Biomass logistics activities, important features and modeling framework

In this section, the key decisions, features and complexities of biomass logistics operations and how different optimization models incorporated these features are reviewed. All the key features reviewed in this section are summarized in Table 1.

3.1. Harvest and collection

Biomass collection deals with procuring the required quantities of biomass from supply areas. It may include harvest operations when biomass is not readily available and must be harvested before collection.

Harvesting is necessary for biomass types such as agricultural residues and energy crops [5,20], and forest-based biomass such as energy wood [21]. Planning the collection of forest residues may not include harvest planning as harvesting for logs is usually planned prior to collecting biomass.

Biomass harvest and collection decisions are taken in both medium-term and short-term planning levels. For medium-term planning, the decisions include selecting the suppliers and determining the quantity of biomass to harvest/collect from each supplier. Short-term planning includes scheduling of harvest and collection equipment to harvest/collect biomass from each supplier.

Biomass collection based on the type of supply chain

Biomass supply chain can be characterized as either a push or a pull system depending on the nature of the collection operation. In a push-based supply chain, the entire quantity of biomass available at each supply area is harvested/collected in a timely manner. A pull-based supply chain is characterized by harvesting/collecting only the required quantity of biomass to meet the demand. We refer to the collection operation in push- and pull-based supply chains as supply-driven and demand-driven collection, respectively.

Supply-driven collection of biomass could be needed when the storage space at supply areas is limited, and the collection must happen within tight time windows. For example, agricultural residues originating from agricultural farms with limited storage capacity must be picked up completely within tight time windows as farms must be prepared for the next plantation season [20]. Wood processing mills have dedicated storage bins with limited capacity for storing the residues. Therefore, timely pickup of these residues is necessary to avoid any interruptions to the mill operations. Due to the restrictions related to timely pickup of biomass, supply-driven collection of biomass is similar to that of industrial and municipal waste collection [22].

Demand-driven collection of biomass, which may result in leaving biomass uncollected at some supply areas, requires sufficient storage capacity at supply areas. Examples of demand-driven collection include the collection of forest residues which are typically left at the harvest sites for several months for natural drying [16,23].

Most of the models developed in the literature considered demand-driven collection of biomass (e.g., [1,5,6]). In these models, the quantity of biomass collected from each supply area was defined as a decision variable subject to constraints that ensured the total demand of biomass was met. Although demand-driven collection may require storage of biomass at supply sites, only few models considered decisions related to the storage at supply sites (e.g., [6]).

While most of the models included only the collection operation, Zhu et al. [24] considered demand-driven harvesting of switchgrass in their optimization model. Their model used continuous decision variables to represent the quantity of switchgrass harvested from each farm during each time period. They assumed harvesting to be performed using harvest units, which comprised of ten laborers, nine tractors, three mowers, three rakes, three balers, and a field transporter as defined by Thorsell et al. [25]. The cost of harvesting was determined by calculating the number of harvest units required to carry out the harvest operations.

Models incorporating supply-driven biomass collection are limited in number. Since the entire quantity of biomass available at each supply area must be collected, decisions in these models include determining whether biomass at each supply area is collected during a time period. For example, Gunnarsson et al. [21] who studied the supply chain of energy wood, modeled supply-driven harvest using binary decision variables to depict if harvesting was done at a supply site during each time period or not. Fixed costs of harvesting and collecting biomass from each supply points were included in their objective function.

Collecting biomass in different forms

Different types of biomass can be collected in different forms. Agriculture residues are generally collected in the form of round bales, square bales or in their chopped form when harvested using a forage harvester [26,27]. Forest residues are collected either loose or bundled [28]. When comminution of forest residues takes place at forest sites, wood chips are collected using appropriate chip trucks. Wood processing mill residues such as sawdust, shavings and wood chips are collected in the same form as they are deposited at mill storage sites.

Although collecting biomass in different forms involves different costs, only few models considered the selection of biomass collection forms as decisions in their models. Zhang et al. [26] considered three different forms of collecting switch grass: round bales, square bales and loose chop. In their model, they assumed that round and square bales could be stored at the supply sites (farms) or delivered directly to the conversion plants. Biomass collected in the form of loose chop was always sent to an intermediate facility for further densification. As a

Table 1
Summary of important features of biomass logistics operations, examples of studies, and how the mathematical models incorporated them.

Logistics operation	Important features	Examples of studies	Modeling aspects/important findings
Harvest/collection	Demand-driven collection	[1,24]	Only the required quantity of biomass was harvested and collected. This was modeled using continuous variables to represent the quantity of biomass collected.
	Supply-driven collection	[21]	The entire quantity of biomass available was harvested and collected. This was modeled using binary variables which assumed a value of 1 if biomass was harvested and collected, and 0 otherwise.
	Different forms of biomass collection	[26,29]	Different costs and deterioration rates were considered for biomass collected in different forms.
	Scattered and seasonal availability of biomass	[6,30]	These aspects have been simplified by assuming the supply quantities of biomass to be given. Supply quantities of biomass were assumed to follow seasonalities.
	Variations in quality characteristics	[33,34]	Uncertainties in biomass quality were incorporated using historical data. Modeling techniques include stochastic programming, scenario analysis and Monte Carlo simulation based optimization.
Storage	Storage of biomass at intermediate facilities	[6,41]	Decisions related to the quantity of biomass to store at intermediate facilities were considered in the models. Storage at intermediate facilities would increase the total cost due to additional transportation and handling costs.
		[21,23]	Biomass storage at intermediate facilities was included as decision variables in the models. Storage at intermediate facilities would result in cost savings due to biomass quality improvement.
	Different types of storage	[23]	Both open-air and under-shed storage of biomass were considered. Decisions related to how much biomass to store under each storage type were considered. Biomass quality would improve with under-shed storage.
	Quality deterioration and dry matter losses	[40,53]	A constant biomass deterioration rate was considered in the inventory balance constraints.
	Risk of fire	[1]	Binary variables were used to determine if storage of biomass exceeded a pre-defined capacity. Cost penalties were considered when the storage exceeded this limit.
	Integration with supply chain design models	[52,53]	Agriculture-based biomass supply chain decisions were integrated with logistics decisions. The models considered binary decision variables for facility location decisions, and the planning horizon was one year.
Transportation	Transportation cost structure	[1,6,40]	Transportation decisions were modeled as the flow of biomass between different locations. Cost parameters for unit flow of biomass were considered to calculate the total cost.
	Inter-modal distribution for long distance transportation of biomass	[31,57]	A combination of trucks and rail was used to transport biomass over long distances. Results related to the benefits of using inter-modal transportation were not discussed.
	Operational level transportation of biomass	[34,56]	Transportation of biomass for a single-day planning horizon was considered using truck routing models.
Pre-processing	Pre-processing agricultural biomass bales	[43,65]	Agricultural biomass bales were assumed to be pre-processed at conversion facilities. Therefore, pre-processing decisions were not considered in the models.
	Trade-off between forest residues pre-processing cost and transportation cost	[6,30]	Pre-processing of biomass was considered at forest areas, intermediate sites and conversion facilities. Results suggested that pre-processing at forest sites was the most economic option.

result, the unit transportation cost parameter considered for loose chop was higher than the other two forms of biomass. However, the optimum solution suggested loose chop as the best harvest method due to lesser dry matter losses and higher density of loose chop-and-densified biomass as compared to round and square bales. Similarly, Larson et al. [29] considered agriculture-based biomass collected as square and round bales. Their optimization model suggested that collecting biomass as square bales was more economical despite higher dry matter losses compared to round bales, due to more efficient storage and transportation of square bales.

Scattered availability of biomass

Scattered availability of biomass within the supply areas is one of the complexities involved in the collection operation. While long distances between the supply sites, storage sites and conversion facilities increase the total transportation distance, the dispersed availability of biomass in several small piles within each supply area complicates the collection process. Since biomass is scattered over the supply area, the collection decisions also include routing of the collection equipment within the supply areas to accumulate the small piles of biomass [27].

Since most of the models developed in the literature dealt with medium-term planning, they assumed the total quantity of biomass available to be given without considering the complexity related to accumulating the piles spread across the areas. However, short-term collection planning models would have to address this complexity by considering the routing of collection equipment between different piles of biomass.

Seasonal availability of biomass

Seasonal availability characterizes forest and agricultural biomass supply. Limited season to harvest agricultural farms results in seasonal supply of agriculture-based biomass [2]. Inaccessibility to forest areas during some months results in seasonal supply of forest residues in countries like Canada [6,23], Sweden [21], Austria [30], and the United States of America [5,31]. Due to the restricted supply season, the collection period of several supply areas may overlap making the collection process equipment- and labor-intensive. The harvest equipment may have to be scheduled among several suppliers under tight time windows making the collection-scheduling complex.

Similar to scattered availability of biomass, complexities related to biomass seasonal availability have been simplified in most of the logistics models in the literature. The total supply quantity of biomass was assumed to vary according to the seasonal availability.

Variations in quality characteristics

Biomass collected from different supply points may have different quality characteristics. Biomass quality and quantity are subject to uncertainties due to several external factors [32]. Since the energy content of biomass depends on its quality, the total quantity of biomass required to meet the demand depends on its quality. This poses additional challenges for demand-driven collection of biomass where the goal is to meet the final demand for energy or fuel. On the other hand, biomass quality characteristics may not impact supply-driven collection of biomass as the entire quantity of biomass must be collected irrespective of its quality.

Few recent studies incorporated uncertainties in biomass supply quality in their models to determine the quantity of biomass to be picked up from each supply location/source [33,34]. Uncertainty in parameters such as moisture content and higher heating values were considered using modeling techniques such as Monte-Carlo simulation based optimization [35], stochastic optimization [33,36] and scenario analysis [34].

3.2. Storage

Storage decisions in the models include the quantity of biomass to be stored and the type of storage system to be used at different locations of the supply chain. The main driver of storing biomass is to match its supply and demand during the entire planning period [8]. Inconsistent supply of biomass resulting from seasonalities and uncertainties present in biomass supply chain makes storage a crucial logistics operation.

Biomass storage decisions are generally taken along with other logistics decisions in the optimization models. Incorporating storage decisions requires models with multiple planning periods where the quantity of biomass stored at the end of each period is considered as a decision variable. Previous models which included storage decisions mostly considered medium-term planning with one year planning horizon and either monthly [6,37] or weekly [5] decisions. The total inventory holding cost in these models was calculated by multiplying the inventory holding cost parameter with the storage quantity at the end of each period. Inventory balance constraints were included in these models to relate the inventory of biomass between consecutive periods of the planning horizon. In these constraints, the inventory at the end of each period was determined using the supply and demand of biomass during that period and the inventory of biomass carried forward from the previous period.

Location of storage

Biomass can be stored at various locations of the network including supply sites, intermediate storage facilities and conversion facilities [16]. Storing biomass at different locations may have different logistical implications. For example, storing biomass at agricultural farms is generally time-constrained as farms may have to be prepared for the next planting season [20,38]. Similarly, storing residues at wood processing mills could be time-constrained due to limited storage space in over-head bins used to store the residues [11]. Due to these restrictions, agricultural residues and mill residues are typically not stored at their respective supply areas for a long time. On the other hand, forest residues may be stored at the forest sites for several months after harvest to reduce the high moisture content through open-air drying [16]. Storage of biomass at conversion facilities may also be constrained by the limited storage capacity [39].

Storing biomass at intermediate storage facilities enables handling and storing large volumes of biomass for long durations [40]. However, storage at intermediate facilities requires additional transportation of biomass, from the supply sites to storage facilities and from the storage sites to conversion facilities [2]. Due to the additional costs for transportation, loading and unloading operations, storing biomass at intermediate storage facilities might increase the total logistics cost [6,41].

Several optimization models considered the storage of biomass at intermediate facilities as decision variables (e.g., [6,42]). In these models, biomass from supply areas could directly be sent to conversion facilities, or to intermediate facilities for storage. A general observation in these studies was that the direct delivery of biomass from supply sites to conversion facilities, whenever possible, was more economical than storing biomass at intermediate facilities to avoid the additional transportation and handling costs at the storage sites. On the contrary, few studies such as Gunnarsson et al. [21] and Gautam et al. [23] reported a decrease in the total logistics cost when biomass was stored at intermediate storage facilities. While the reason for this cost reduction was not specified in [21], Gautam et al. [23] highlighted that cost reduction was possible due to the improvement in biomass quality when it was stored at intermediate facilities.

Most of the models in the literature dealt with biomass storage only in the upstream of the supply chain which includes biomass supply sites, intermediate storage and conversion facilities. Relatively few models considered the downstream of the supply chain where the biofuels could be stored (e.g., [5,43]). Storage of biofuel at biorefineries and demand points were included as decision variables in these models. Similar to the inventory balance constraints for biomass, inventory balance constraints for biofuel storage were included in the models.

Type of storage

Depending on the biomass type and the climatic conditions, different types of storages such as covered and open-air storages can be used to store biomass [16]. Covered storage is used for storing dried biomass, whereas open-air storage is used for biomass with higher moisture content [16]. Biomass stored in covered facilities may have additional options such as hot air injection to dry biomass further [2]. The type of storage influences the characteristics of biomass such as its moisture content [44]; therefore, selecting the type of storage is an important logistics decision.

While storage decisions were considered in several optimization models, they mostly assumed the type of storage to be pre-determined, and did not consider the selection of appropriate storage type for reducing the total cost. Recently, Gautam et al. [23] considered two types of storages to store biomass at intermediate facilities. They were storage in an open-air terminal and storage under a shed in a depot. Their optimization model was used to assess the costs of incorporating a terminal with both open-air storage and under-shed storage in delivering forest-based biomass from forest sites to biorefineries. They assumed that the quality of biomass could be improved by storing it under a shed in a depot. In their model, biomass could either be sent directly from the open-air terminal to biorefineries, or be transferred from the terminal to the under-shed storage. Their model was used to determine the quantity of biomass to be stored in each storage type and the quantity of biomass to be transferred from open-air storage to the closed shed during each period.

Biomass quality deterioration and dry matter losses

While storage of biomass is essential to maintain a consistent supply of feedstock, biomass dry matter losses caused due to quality deterioration is a risk associated with storing biomass for a long duration [45]. Biomass stored for long periods of time may undergo decay, and as a result, it may not be useful in the conversion process [43].

Several models considered biomass deterioration due to storage by assuming a constant rate of deterioration between consecutive time periods in their models (e.g., [5,43]). Quality deterioration in biomass was incorporated in these models by determining the net volume of biomass that was available during each period. The volume of biomass available during each period was determined by multiplying the inventory forwarded from the previous period with the deterioration rate. While biomass deterioration was incorporated in these models, the focus of the studies was on applying the models to case studies or on developing solution methodologies to find the optimum solutions. The impact of incorporating biomass deterioration in the models was not evaluated.

Biomass deterioration and the resultant dry matter losses can be controlled by altering the type of storage used [8]. For example, Rentizelas et al. [2] described three types of biomass storages, namely, closed warehouse with external drying, covered storage without external drying, and ambient storage covered with a plastic film. Each of these systems have different rates of material loss with storage under closed warehouse with external drying having the least dry matter loss (almost negligible) and ambient storage having the maximum loss. However, no optimization models incorporated decisions related to selecting storage type to control biomass deterioration and dry matter losses.

Risk of fire

Storing biomass for long duration may pose a risk of fire due to the internal heat generated as a result of respiration of living cells in biomass [46]. Risk of fire due to storing large quantities of biomass has not been incorporated in most of the biomass logistics models in the literature. Shabani and Sowlati [1] incorporated this aspect indirectly by including cost penalties when biomass storage exceeded a certain limit. This was modeled using binary variables which assumed a value when the storage level exceeded the limit. These cost penalties were included in the model as additional personnel and handling charges may be required if storage of biomass exceeds a certain limit.

Integrating biomass logistics models with supply chain design models

Forest residue supply chain design models require long planning horizons spanning over 10 years (e.g., [47,48]) or more (e.g., [49,50]) with yearly decisions. The resultant supply chain design models used aggregated data with yearly supply and demand of biomass. Due to the data aggregation over yearly time steps, storage decisions, which are generally considered for weekly or monthly time steps, have not been included in these models. Therefore, in the case of forest residue supply chains, strategic level supply chain design decisions have generally been taken separately from logistics decisions.

While most of the forest-based biomass supply chain design models considered long planning horizons, few design models included decisions related to the location of temporary storage yards over a one-year planning horizon (e.g., [30,51]). Due to the temporary nature of harvest sites in forest residue logistics, the location of intermediate storage and pre-processing yards have been considered for one-year planning horizon in these models.

In the case of agriculture-based biomass, one-year planning horizon is sufficient to incorporate both supply chain design and logistics decisions in the models as the crop rotation cycle is short and the locations of the farms are fixed. Therefore, numerous agriculture-based biomass logistics models included facility location decisions along with storage and transportation decisions (e.g., [52,53]).

3.3. Transportation

Transportation deals with the movement of biomass between different locations of the network. High transportation cost due to long transportation distances is observed as one of the main contributors for the high biomass logistics cost. Moreover, due to its low energy density, large quantities of biomass is required to meet the demand, and as a result the total cost is increased [2,54].

Transportation decisions are made for both medium-term and short-term planning levels. For medium-term planning, the decisions include the quantity of biomass to be transported between different locations per period, which is typically a month or a week (e.g., [5,6]). When multiple modes of transportation are used, the decisions also include the selection of the mode of transportation (e.g., [55]). Transportation of biomass for short-term planning deals with allocating biomass from supply points to demand points over a short-term horizon such as a week or a day, and developing daily truck routes and schedules to carry out biomass pickup and delivery operations (e.g., [34,56]).

Cost structure

The cost of transporting biomass depends on several aspects such as the transportation mode, distance traveled, quantity of biomass transported, number of truck/rail/barge loads used, and the actual routes taken by the vehicles. The cost of loading and unloading biomass from these vehicles also contributes to the total transportation cost. Incorporating all these attributes into the optimization models could get complicated.

Most of the optimization models in the literature simplified the cost estimation by assuming transportation cost parameters such as transportation and loading/unloading costs per unit flow of biomass (e.g., [40,57]). Transportation-related costs were included in the objective functions in the models by multiplying the total flow of biomass with the cost parameters. While most of the models assumed the values of the cost parameters to be given, few studies explained how these values were determined. In these studies, it was assumed that trucks always traveled round-trip between pickup and delivery points, where trucks traveled empty from delivery points to pickup points (e.g., [2,58]). The transportation cost per unit quantity of biomass used in these models was calculated by dividing the round-trip transportation cost by the capacity of the vehicle.

Long distance transportation of biomass

Different modes of transportation such as truck, rail and barge are used to transport biomass. Trucks, which are used widely for biomass transportation, are found to be economical only when the transportation distances are short [57,59]. Rail and barge are considered cost-effective for long distance and high volume transportation of biomass [31,60]. However, the use of these modes may be restricted due to the limited access of biomass supply and demand locations to these modes of transportation.

Inter-modal transportation, which uses a combination of different transportation modes, can be an alternative for long distance and high volume transportation of biomass when biomass supply or demand locations have limited or no access to rail or barge (see, [57,60]). In this distribution system, biomass is picked up from supply sites using trucks and delivered to inter-modal transshipment points which have access to different transportation modes. Biomass from these transshipment points can be transported over long distances using rail or barge either directly to conversion facilities if possible, or to other inter-modal transshipment points. Trucks can be used for the final delivery of biomass from the transshipment facilities to conversion facilities. Since the capacity of rail and barge is greater than that of trucks, multiple truckloads of biomass can be consolidated for one load of rail or barge. This type of distribution network where shipments of smaller size are sent to a consolidation center, and larger shipments are sent from there to the destinations is called hub-and-spoke network. While inter-modal transportation of biomass over hub-and-spoke networks may be cost effective, the logistics planning problem becomes more complex due to additional handling operations at transshipment points and scheduling of multiple transportation modes. Moreover, these modes demand high fixed costs and require specialized terminals and infrastructure [61]. Economic feasibility studies and strategic level plans are required to design and plan inter-modal transportation of biomass.

Several recent models considered long-distance transportation of biomass over hub-and-spoke networks using combinations of different modes of transportation (e.g., [31,57]). All these models considered one-year planning horizon and assumed that the required infrastructure for transportation using rail or barge was already present. As a result, infrastructure setup costs were not included in the models. Most of these studies considered trucks for transporting biomass from supply points to the inter-modal transshipment centers, and trains for transporting biomass from the transshipment centers to conversion facilities. The focus of these studies was on developing solution methodologies to solve the optimization models and comparing different solution approaches. They did not investigate the benefits of using inter-modal transportation over using a single mode of transportation.

Use of pipelines is another alternative to transport biomass over long distances. However, biomass transportation using pipelines is less explored in the literature due to certain inherent complexities and issues. In order to transport biomass using pipelines, biomass in its ground or chipped form must be mixed with a carrying fluid such as water or oil [62]. Therefore, pipeline transportation of biomass is not compatible with combustion-based conversion technology due to a potential decrease in the lower heating value of biomass resulted from the carrier fluid [63]. Moreover, transporting biomass using pipeline may also require truck delivery of biomass to the inlet of the pipeline [62], making the decision making complex due to the underlying hub-and-spoke distribution network. In addition, implementing pipeline transportation may require high investments. Given the low value of biomass, such high investments may not be justified.

Short-term transportation planning

Optimization of biomass transportation over a short-term period received limited attention in the literature. To the best of our knowledge, the current models dealt only with routing of trucks for transporting forest-based biomass for a single day planning horizon. Han and Murphy [56] who considered the transportation of biomass in full-truckloads assumed that the pickup and delivery locations of each truckload were fixed. The resultant transportation orders were met using a heterogeneous fleet of trucks with different characteristics. For a given set of transportation orders, their model was used to determine optimal truck routes with the least cost. On the other hand, Zamar et al. [34] developed a model to determine the optimal truck routes to collect residues from a set of sawmills and deliver them to a storage site. Since there was only one destination, there were no transportation orders in their model. However, unlike Han and Murphy [56], their model considered that trucks could pick up residues from multiple sawmills to accumulate full truckloads of biomass, and considered variations in biomass quality.

3.4. Pre-processing

Biomass pre-processing includes operations such as sorting, grinding/chipping, drying and densification [64]. Pre-processing is done in order to increase the transportation efficiency and improve the feedstock quality [8,64].

Biomass may or may not require additional pre-processing operations depending on its type and the harvesting method [64]. Agriculture-based biomass is generally collected as bales which may require grinding operation before densification or conversion into energy and fuel. On the other hand, agriculture-based biomass collected using forage harvester is already in its comminuted form, and it could be used directly. Forest-based biomass may or may not require comminution depending on the type of residues. Harvest residues such as non-merchantable logs, tops and branches which are larger in size require comminution before they are used in the conversion process. On the other hand, mill residues including sawdust and shavings do not need comminution as they are in a usable form.

Biomass pre-processing includes decisions related to the location and the type of pre-processing, the quantity of biomass to be pre-processed, and scheduling the pre-processing operations. Pre-processing of biomass has mostly been considered along with transportation and storage decisions in the optimization models. While biomass pre-processing includes drying and densification as well, most of the models only looked at grinding and chipping decisions.

Pre-processing of agriculture-based biomass

Transportation and storage of agriculture-based biomass bales are considered efficient. Therefore, bales are generally pre-processed at the conversion facilities before they are used further. As a result, pre-processing decisions were not included in most of optimization models dealing with agriculture-based biomass (e.g., [43,65]).

Pre-processing of forest residues: trade-off between pre-processing cost and transportation cost

Forest residues including harvest residues and non-merchantable logs require pre-processing before they are used in the conversion process. Forest residues can be pre-processed at the forest areas, intermediate facilities, or at conversion facilities [16,66], and there could be a trade-off between the pre-processing cost and transportation cost. Transportation of pre-processed biomass is considered more efficient due to the increase in biomass density [64,67]. Thus, pre-processing of biomass at forest sites and transporting them to storage or conversion facilities would be the most efficient strategy for reducing transportation-related costs. However, this requires equipment such as mobile chippers and grinders which have higher costs and lower efficiencies compared to stationary equipment at storage sites or conversion facilities [67]. As a result, pre-processing of biomass is more efficient at intermediate facilities or conversion facilities.

Pre-processing of forest residues at supply sites, intermediate facilities, and conversion facilities was considered in few models in the literature (e.g., [6,41]). Pre-processing costs were assumed to be different at different locations. Although pre-processing biomass at intermediate facilities is considered more efficient, these models suggested that pre-processing biomass at forest sites as the most economical option as pre-processing and storing biomass at intermediate facilities require additional handling and transportation operations.

While few studies demonstrated pre-processing of biomass at forest sites to be an option to improve transportation efficiency, there are practical complexities to implement this option at the operational level. One of the complexities is associated with the inaccessibility of large chip trucks that carry wood chips to forest sites [68]. Few models addressed this issue by considering moving biomass from harvest areas to concentration yards using smaller trucks, where the concentration yards are within the harvest area but more accessible to the road. Biomass was pre-processed at the concentration yards and transported to conversion facilities using large chip vans [28,69].

As described in this sections, biomass logistics is characterized by complex and inter-dependent operations. Different complexities specific to each logistics operation exist at different levels of planning. Recent literature witnessed an increase in the number of studies which incorporated several practical complexities in their optimization models. Section 4 reviews recent trends in biomass logistics optimization literature which addressed few complexities in biomass logistics.

4. New trends in biomass logistics optimization

In this section, models that demonstrated novelty in addressing the complexities in each logistics operation are reviewed. Table 2 provides a summary of these studies.

4.1. Harvest and collection

Scattered availability of biomass in several piles across supply areas

Since most of the models developed in the literature dealt with medium-term planning, they simplified the complexity related to accumulating several small piles of biomass spread across the supply areas. Recently, Zamar et al. [27] addressed this issue in their model which focused on optimizing the collection of biomass from agricultural farms over a one-day planning horizon. They developed two optimization models where the first model was used to partition the bales spread across the field into several clusters. Bales in each cluster were assumed to be collected together and brought to a roadside storage site. The second model was a variant of the Vehicle Routing Problem where the bales collection equipment was routed in each cluster to collect bales with the least routing cost.

Allocating biomass collection equipment among several supply areas

Seasonal availability of biomass poses challenges in short-term collection planning of biomass. Collection season may overlap for several suppliers necessitating careful allocation of the collection equipment among them. Recently, Aguayo et al. [20] studied the collection of corn-stover from several agricultural farms which had overlapping harvesting periods using limited equipment. They assumed that one conversion facility was responsible for managing the harvest and collection operations at all agricultural farms. They developed an optimization model which included decisions related to allocation of different types of collection equipment to the farms and the routing of equipment between the farms.

Incorporating variations in biomass quality and quantity in optimization models

Most of the previous studies which incorporated uncertainties in their models dealt with variations only in biomass quality characteristics. Another source of uncertainty in biomass logistics, which was not included in most of the previous models, is quantity of biomass supply.

Table 2
Summary of new trends in biomass logistics optimization models.

Logistics operation	Novelty	Study	Modeling aspects/important findings
Harvest/collection	Scattered availability of biomass in several piles across the supply areas	[27]	Biomass piles were partitioned into several clusters, and the collection equipment was routed in each cluster to collect biomass.
	Allocating collection equipment among several supply areas	[20]	Biomass collection equipment was allocated to different suppliers. Once collection at a supplier was finished, the equipment was routed to other supply areas.
	Uncertainties in biomass supply quality and quantity	[33,70]	Huang et al. [70] developed a stochastic programming model, and Shabani and Sowlati [33] developed a hybrid stochastic programming and robust optimization model to incorporate biomass supply variations.
	Variations in biomass quality in short-term planning	[34]	Quality variations in biomass collected from sawmills was modeled using scenario analysis.
	Integration with GIS	[71–73]	Accurate biomass supply quantities and travel distances were retrieved using GIS and were used within the optimization models.
Storage	Biomass deterioration rate varying with time	[29]	Biomass deterioration was assumed to decrease with time. Therefore, the optimal solution suggested to use freshly harvested biomass over biomass which had been stored for a while.
	Integrated forest residue supply chain design and logistics modeling	[75]	An integrated supply chain design and logistics planning model with 20-year planning horizon and monthly time steps was developed.
Transportation	Cost for each vehicle load of biomass	[57,77]	The flow values were defined as number of vehicle loads. Transportation cost was associated with each vehicle load of biomass.
	Emissions from logistics operations	[52,57]	Models minimizing total emissions suggested to install multiple conversion facilities as opposed to models minimizing the total cost which suggested setting up a single facility with large capacity. This was due to the reduction in emissions from transportation when multiple facilities were installed.
	Effect of carbon emission regulatory policies	[55,79]	Considering emissions from different modes of transportation, the models selected suppliers (based on the mode of transportation available) under different carbon emission regulatory policies.
	Long distance transportation using barge and truck	[60]	Barge was used to transport wood pellets from supply areas to transportation hubs. Trucks were used to transport wood pellets from the hubs to conversion facilities. 8% increase in total profit was reported when barge and truck were used compared to using only trucks.
	Uncertainty in transportation hub availability	[81]	Transportation hubs had different probabilities of disruptions due to natural disturbances. The model was used to select the transportation hub that minimized total cost.
	Traffic congestion due to transportation of biomass	[31,83]	Traffic congestion on roads due to biomass trucks/rail was considered in [82,83]. Marufuzzaman and Ekşioğlu [31] considered congestion at multi-modal transportation hubs by defining a congestion index and an associated cost.
	Road maintenance to procure forest residues	[23]	Additional cost was incurred when biomass was procured from forest sites due to road maintenance. The optimal solution suggested storing biomass at a storage facility to avoid the road maintenance cost.
	Short-term transportation in multi-tier supply chain	[77]	All truck types could be used in different tiers of the supply chain. The optimal solution suggested shorts trucks be used for short distance and larger trucks be used for long distance travels.
Pre-processing	Pre-processing agriculture-based biomass at intermediate facilities	[52,84]	Agriculture-based biomass was densified into pellets at central depot before delivering them to the conversion facilities. The total cost was lower when biomass was densified at central depots compared to when bales were directly delivered to the conversion facilities.

Few recent models accounted for variations in both supply quality and quantity of biomass in their models (e.g., [33,70]). Huang et al. [70] modeled the variations in biomass supply by assuming a set of scenarios with pre-defined probabilities in their stochastic programming model. Shabani and Sowlati [33] developed a hybrid stochastic programming and robust optimization model, where stochastic programming was used to model uncertainties in biomass quality and robust optimization technique was used to model variations in biomass supply.

Incorporating variations in biomass quality in short-term logistics planning

Studies that considered variations in biomass quality mostly focused on medium-term planning. However, variations in biomass quality also influence the collection and transportation operations over a short-term such as a day or a week. Recently, Zamar et al. [34] addressed this issue by incorporating variations in biomass quality in their vehicle routing model. The model they developed was used to determine truck routes to collect residues from sawmills and deposit them at a storage yard. Variations in biomass quality were modeled using scenario analysis, where each scenario was defined by randomly drawing values for uncertain parameters from their probability distributions. Due to variations in biomass quality, the objective function of their model was to maximize the energy return on energy invested for routing the trucks.

Integration with GIS

A trend of incorporating geographic information systems (GIS) in optimization models to get accurate information about biomass supply quantities and traveling distances can be observed in the literature (e.g., [71–73]). While the optimization models in these studies is similar to those in other studies without GIS, integration with GIS enhances the accuracy of input data, and visualization of data and results [73].

4.2. Storage

Biomass dry matter loss rate varying with time

Biomass dry matter loss rate due to storage was mostly considered in numerous models by assuming a constant rate of deterioration per period. However, biomass dry matter loss rate increases at a decreasing rate in storage [74]. These losses increase the requirement of biomass at the conversion facility to meet the demand. Larson et al. [29] incorporated this aspect in their model by defining a cost component for transporting additional biomass to the conversion facility due to dry matter losses. Freshly harvested switchgrass was considered to have a higher rate of loss as compared to biomass that has been harvested and stored for a while. Under this assumption, their optimization model suggested a last-in first-out strategy for using biomass as larger quantities of freshly harvested biomass deteriorate faster compared to biomass that has been in storage for longer periods.

Integrated forest residues supply chain design and logistics optimization

Several studies dealing with agriculture-based biomass considered supply chain design and logistics decisions together in a single model with one-year planning horizon. However, developing such integrated models for forest residues supply chain requires long-term planning horizon spanning over several years due to the long growth cycle of forest-based biomass and the temporary nature of forest sites locations. Due to this reason, forest-based biomass supply chain design decisions have typically been taken separately from logistics decisions in the literature. Recently, Akhtari et al. [75] demonstrated that supply chain design decisions, when taken separately from logistics decisions, may result in infeasibilities as prescribed by the medium-term logistics models. To tackle this issue, they developed an integrated model, with 20-year planning horizon and monthly time steps, where supply chain design and logistics decisions were taken together in a single model. As a result, possible logistical infeasibilities due to supply chain design decisions were eliminated.

4.3. Transportation

Transportation cost for each vehicle load of biomass

Transportation decisions have been included in most of the biomass logistics models as flow volumes, and the transportation cost was calculated using parameters such as cost per unit flow of biomass. However, estimating the cost using such parameters does not account for other cost components such as fixed costs associated with each truck/rail/barge load.

One way to incorporate these fixed costs is to consider flow quantities in number of vehicle loads, and include the cost for each vehicle load as done by Wu et al. [76] and Malladi et al. [77]. Another modeling approach to incorporate fixed costs, as considered by Roni et al. [57], is to consider a step-wise cost function. Their cost function included two components: (1) fixed cost for each rail car, and (2) variable cost depending on the quantity of biomass transported. For a given quantity of biomass, equivalent number of rail cars required for the transportation was calculated, and a fixed cost for each of them was added to the objective function along with the variable cost for transporting each unit of biomass. While such cost structure that accounts for the number of vehicle loads can better estimate the total cost, the benefits of using such a structure over using the simplified cost structure have not been reported in the literature.

Multi-objective optimization incorporating emissions from logistics operations

Along with the economic objective of minimizing the total cost, environmental objective function of minimizing the total emissions due to logistics operations has been considered in few studies [52,57]. Ng and Maravelias [52] included emissions due to biomass harvesting, pre-processing, conversion process and transportation in their model which dealt with determining the locations of the conversion facilities and intermediate depots for pre-processing biomass. They concluded that setting up a single conversion facility was the most economical solution, while setting up two facilities was shown to have lower emissions due to shorter transportation distances. However, they did not consider total emissions due to setting up the two facilities while the economic objective function included cost due to facility setup. A similar observation was made in the study by Roni et al. [57] whose single-objective model with cost minimization suggested to set up single facility of large capacity as opposed to their multi-objective model with economic, environmental and social objectives which suggested multiple facilities of smaller capacities. Moreover, their cost minimization model suggested increased use of trucks to avoid capital costs for setting up rail hubs, whereas their multi-objective model suggested increased usage of rail for transporting biomass as it created more jobs and reduced total emissions. They included total emissions from biomass transportation, biofuel production and setting up transportation hubs in their environmental objective function.

Transportation planning under different carbon emission regulatory policies

Few recent studies investigated the impact of carbon emission regulatory policies on biomass logistics operations. Currently, there are four carbon emission regulation policies considered in the literature and implemented by several governments: carbon cap, carbon cap and offset, carbon cap and trade, and carbon taxing [55,78]. In the carbon cap policy, total emissions are limited to a maximum quantity, and in the carbon cap and offset policy, the total emissions can exceed the maximum capacity with a penalty. Trading emissions with other players of the supply chain defines the carbon cap and trade policy. The total emissions are not limited to any capacity and cost is associated with every unit of emission in the carbon taxing policy. Studies which modeled biomass logistics under different carbon policies performed sensitivity analyses with respect to different parameters such as carbon price and carbon cap. Palak et al. [55] developed models to select suppliers where each supplier could have access to trucks, rail, or barge. Considering emissions from transportation and biomass storage, they concluded that the selection of suppliers depends on the carbon policy considered. In similar lines, Memari et al. [79] studied the effect of carbon tax and carbon cap-an-trade policies for supplying biomass from suppliers to several CHP plants. They observed that a linear increase in carbon price would lead to non-linear reductions in total emissions. While the effect of different policies on biomass logistics operations was investigated, the objective of these studies was not to compare different carbon regulatory policies.

Long distance transportation of biomass using barge and truck

Several recent studies developed models for optimizing long distance transportation of biomass over hub-and-spoke networks. These studies assumed biomass transported from supply areas to transportation hubs using trucks, and from the hubs to conversion facilities using rail. Unlike these studies which used a truck-rail combination, Andersen et al. [60] considered distribution of wood pellets using barge-truck combination. Barge was used to transport wood pellets from a pellet plant close to a port to storage sites at other receiving ports. Trucks were used to distribute pellets from storage sites to customers. Their results demonstrated an 8% increase in the profit margin when the barge-truck combination was used as compared to distribution only using trucks. Similar to the other studies, their study did not include the capital costs required to set up and maintain the ports.

While most of the studies which considered transporting biomass over long distances considered the transportation modes to be fixed in each tier of the supply chain, Lin et al. [80] compared 15 different scenarios by considering five transportation mode configurations and three pre-processing techniques at intermediate storage facilities. They considered rail or trucks as the two possible modes of transportation in each tier of the supply chain. While this study did not develop optimization models to select the best distribution configuration, the results pointed towards some interesting observations. They concluded that production of ethanol at conversion facilities closer to the supply sites, and distribution of ethanol over long distances was the most economical configuration. Their results also suggested that biomass transportation using trucks over short distances and ethanol transportation using rail over long distances was the most desirable option.

Uncertainties in transportation hub availability

Studies on biomass logistics which considered biomass transportation using multiple modes for long distance transportation assumed the transportation hubs to be available always. However, in regions such as Southeast United States, severe weather conditions and natural disturbances like floods and hurricanes can disrupt the transportation network, and the transportation hubs may not be available always. Marufuzzaman and Ekşioğlu [81] considered disruptions in transportation infrastructure due to natural disturbances in their optimization model. They considered the transportation of biomass using barge and rail for a case study in Southern United States. For given probabilities of disruptions, their model determined the transportation hubs to be used during each period of the planning horizon while minimizing the total cost.

Traffic congestion due to biomass transportation

With ambitious biofuel-production targets, and due to trucks being the most economical and practical mode for transporting cellulosic biomass over short distances, it is expected that biomass transportation may result in an increased traffic congestion on the road networks [82]. Studies such as Bai et al. [82] and Hajibabai and Ouyang [83] considered traffic congestion due to increased biomass and biofuel shipments in their network design models by assuming pre-defined public traffic in the transportation network. Further, Hajibabai and Ouyang [83] included decisions related to expansion of highway lanes to access the conversion facility to cope with traffic congestion.

Congestion at transportation hubs with limited capacity for transporting biomass over long distances using multiple modes of transportation was recently considered in a supply chain design and logistics model by Marufuzzaman and Ekşioğlu [31]. The key decisions in their model were regarding using a multi-modal transportation hub during each period. Each transportation hub had a capacity, and the system was considered congested as the flow of biomass through a hub got closer to its capacity. This was incorporated using a congestion index defined as the ratio of total flow through a hub and the remaining capacity of the hub. A congestion cost factor was multiplied with the congestion index to quantify the cost of congestion. The cost of congestion was included in the objective function of their model.

Road maintenance for transporting residues from forest areas

Due to the dynamic nature of harvest sites whose locations may change over time, roads used to procure harvest residues are temporary in nature [23]. These secondary and tertiary roads, which are mainly constructed for logging activities, have short durability and may undergo deterioration necessitating additional road maintenance. This maintenance cost adds more to the cost of collecting forest residues. Gautam et al. [23] included the cost of maintaining the secondary and tertiary roads whenever biomass was procured from forest areas in the objective function of their model. It suggested that the road maintenance cost could be avoided by storing biomass at terminal storage sites. In addition, it was shown that the storage and handling costs at terminal storage sites was lower than the road maintenance cost to access forest areas.

Short-term transportation planning in a multi-tier supply chain

Previous studies on short-term biomass logistics optimization are limited, and they considered transportation only from supply points to either a single [34] or multiple demand points [56]. However, forest-based biomass supply networks generally involve multiple tiers between supply points, intermediate storage sites and demand points. Moreover, the same fleet of vehicles could be used in all tiers of the supply chain. In a recent study, Malladi et al. [77] studied the transportation of multiple types of forest-based biomass in a real case study involving multiple supply sites, an intermediate storage yard and multiple demand points. Their study considered different types of trucks, and direct delivery of biomass from supply sites to demand points was permitted depending on the biomass type. They concluded that the optimal solution prescribed more direct delivery of biomass compared to transporting biomass to the storage site. Furthermore, they stated that it was more cost effective to use smaller trucks for short distances and larger trucks for long distances.

4.4. Pre-processing

Pre-processing of agriculture-based biomass at intermediate facilities

Agriculture-based biomass is generally collected in the form of round or rectangular bales. The transportation and storage of bales is considered efficient. Therefore, most of the studies assumed that bales are pre-processed at the conversion facilities. As a result, pre-processing decisions were not included in the logistics models. Ng and Maravelias [52,84], on the contrary, considered the densification of corn-stover and switchgrass into pellets at central depots before delivering the feedstock to conversion facilities. They developed optimization models to determine the locations of central depots where biomass could be densified along with other logistics decisions such as transportation and storage of biomass. Due to the densification of biomass, it was concluded that the total logistics cost was lower in the presence of a central depot when compared to the system without it.

5. Discussion

There have been numerous studies on biomass supply chain optimization, and those focusing on logistics operations belong to medium-term and short-term planning levels. Biomass logistics planning involves decisions related to harvest and collection, storage, transportation and pre-processing operations. A multitude of practical challenges complicates biomass logistics planning, and numerous recent optimization models incorporated some of these complexities.

Logistics models differ depending on the type of biomass that is considered. Agriculture-based biomass is collected from agricultural farms. The crop rotation cycle in agricultural farms is typically few months with alternating plantation and harvest operations. Due to the fixed location of farms and short rotation cycle of crops, models with one-year planning horizon and monthly or weekly decisions can be used to optimally plan agriculture-based biomass logistics and design the supply chain. On the other hand, forest-based biomass such as harvesting residues and energy wood are available at forest areas where harvesting is done [85]. Areas for logging and harvesting of trees are determined in harvest plans and generally change over time. Due to changes in supply location and multiple-year crop rotation cycle, forest-based biomass supply chain design models require multiple-year planning, while the logistics planning requires models with shorter planning horizons. These differences in forest-based and agriculture-based biomass logistics result in different complexities and optimization models.

Biomass logistics operations are inter-dependent and the models developed in the literature considered multiple logistics operations. Studies focusing only on a single logistics operation are rare. Biomass transportation and storage operations have been included in most of the models, while fewer models included harvest and pre-processing operations. Models for short-term planning mostly focused on specific operations such as transportation [56] and collection operations [27].

Biomass logistics not only influence the economic performance of the system, but also affect social and environmental sustainability. As a result, an increasing number of studies started to consider environmental and social considerations in biomass supply chain design models using multi-objective optimization [10]. While considering environmental and social objectives at strategic level are crucial for designing sustainable supply chains, considering them in logistics models is necessary for managing them sustainably. However, relatively few studies incorporated environmental and social concerns in biomass logistics models (e.g., [57]). This has been identified as a gap in the literature in a recent review article by Melis et al. [86] as well.

Environmental concerns related to emissions from logistics operations have been considered in few recent studies by incorporating different carbon emission regulatory policies in their models (e.g., [55,79]). A general observation in these studies was that an increase in carbon price or decrease in carbon cap results in emission reduction. While these studies investigated the impact of different carbon policies on biomass logistics, challenges and feasibility of implementing them have not been discussed. For instance, the carbon cap-and-trade policy in Ontario, Canada is currently imposed only on electricity importers, natural gas facility or distributor that emit 25,000 t of GHG emissions per year, and fuel suppliers that sell more than 200 l of fuel per year to participate in the program [87]. Individual fuel consumers such as biomass logistics companies are currently not included in the cap-and-trade scheme. Therefore, studying the impact of the cap-and-trade scheme could be more relevant when end-users of fossil fuels participate in carbon trade market. On the other hand, modeling the impact of different carbon tax rates on biomass logistics is more relevant at present as the end users of fossil fuels are responsible for paying carbon tax for their emission.

Several models which included biomass storage operations incorporated biomass deterioration by using a fixed rate of biomass deterioration per time period (e.g., [40,43]). However, changes in moisture content, which is an important characteristic of biomass, has not been incorporated in most of them. Biomass moisture content depends on several external factors such as climate and type of storage. Incorporating them in mathematical models requires a lot of data and the mathematical relationship between moisture content and the external factors. The resultant mathematical models may be non-linear and difficult to solve.

Depending on the type of biomass considered, biomass may or may not require pre-processing operations. Models that dealt with forest-based biomass such as harvest residues and non-merchantable logs included pre-processing decisions either at intermediate facilities or at the supply sites (e.g., [6]). Studies that considered biomass types such as sawdust and wood chips did not include pre-processing decisions (e.g., [1]). Due to transportation efficiency, agriculture-based biomass bales are generally pre-processed at conversion facilities. Since the focus of most of the previous papers has been on optimizing upstream logistics of biomass to the gate of conversion facilities, models dealing with agriculture-based biomass did not include pre-processing decisions (e.g., [43]).

Most of the papers which studied long distance transportation of biomass validated and evaluated their models using publicly available data for conversion facilities which do not exist in reality. While the results obtained from these studies could provide some insight into various aspects of the logistics systems, testing the models using real data is necessary to show the applicability of the models. With numerous bio-conversion plants being installed worldwide, it is timely to evaluate the models using data from real case studies. However, due to the long planning horizons and the large quantity of data required to evaluate the models, data collection process could be complex and challenging.

5.1. Future work

Previous studies on biomass logistics indicated that social concerns related to increased traffic due to biomass trucking in urban areas could be important in designing and planning biomass supply chains [88]. While few previous studies incorporated traffic congestion in biomass logistics (e.g., [31]), the developed models considered medium-term plans focusing on the design of the supply chain with multi-modal transportation. Future models could incorporate social aspects related to traffic congestion in biomass logistics for short-term planning. These models could also optimize the feedstock mix where more energy-dense feedstock such as wood pellets could be used to reduce the required number of biomass truckloads at conversion facilities.

Current studies on biomass logistics mostly considered fossil fuels for transporting biomass. Although utilizing biomass is considered good for the environment, the amount of fossil fuel consumed for biomass logistics may offset the emission reduction from using biomass at conversion facilities [89]. While models which minimize total cost of logistics also result in emission reduction [77], further reduction in total emissions could be possible by utilizing alternative fuels such as bio-ethanol and bio-diesel. However, utilizing alternate fuels for transportation may require an upgrade of truck engines which could be expensive [89]. Future models could be developed to assess the green performance of using alternate fuels for transporting biomass [89]. From a policy perspective, the developed models could determine optimal fuel mix for transporting biomass under different carbon emission policies.

Several studies in the literature that evaluated the trade-off between economic and environmental objectives of biomass supply chain concluded that minimizing total emissions was inversely related to maximizing the total profit of the supply chain [90]. However, the relationship between economic and environmental objectives could depend on the adopted carbon emission policies [91]. It might be interesting to consider the environmental performance of biomass logistics under different carbon emission policies and evaluate the trade-offs between economic and environmental objectives.

With more bio-conversion facilities in operations, an increasing number of models are being developed for short-term logistics planning (e.g., [20,34,77]). The current literature on short-term planning of biomass logistics is nascent, and multiple avenues exist for future research. Incorporating logistics operations in short-term planning models requires addressing several practical challenges such as restricted operation time windows, limited availability of equipment, and synchronizing several inter-dependent operations. To consider these practical aspects, the models have to address detailed scheduling of logistics operations. The resultant models could be very large and may require special solution techniques to solve them to optimality. Moreover, user-friendly decision support tools could be developed for decision makers to enhance the applicability of the models.

Current studies which considered biomass storage simplified the storage operations by assuming a maximum storage capacity and making sure that biomass inventory does not exceed the storage capacity. This inventory policy is called the Maximum Level policy [92]. There are other inventory policies that are adopted in different logistics systems such as the order-up-to policy, where biomass is replenished to fill the inventory capacity [93], and fixed-order quantity policy, where a fixed quantity of biomass is ordered. While no current study modeled and evaluated them, it could be interesting and useful to investigate the effect of different inventory policies on biomass logistics in future models.

6. Conclusions

This paper provided a comprehensive review of key features of biomass logistics, how different optimization models incorporated these features, and the new trends in biomass logistics optimization models. Logistics operations were categorized into biomass collection and harvesting, storage, transportation and pre-processing. The new trends in optimizing biomass logistics involve incorporating several practical features such as limited equipment availability, varying biomass deterioration rates, increase in traffic congestion, uncertainties in biomass supply, and emissions due to logistics operations into mathematical models. The literature on short-term biomass logistics optimization is nascent with many avenues for future research. Short-term planning requires detailed scheduling of logistics operations with practical constraints related to operational time window, limited equipment availability and inter-dependency between the operations. While most of the literature on multi-objective biomass supply chain optimization focused on supply chain design, models for logistics planning should be developed to ensure sustainable management of the supply chain. Future models could incorporate social concerns related to traffic congestion due to biomass trucking in urban areas as social concerns could be crucial for installation and operation of bio-conversion facilities. With many countries adopting different carbon regulatory policies, future models could be used to study the trade-off between economic and environmental objectives under different carbon emission policies. Models could also be developed for optimizing the fuel mix to be used for transporting biomass under different carbon regulatory policies.

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