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

Krishna Teja Malladi[a], Taraneh Sowlati[b,*]

[a] Industrial Engineering Research Group, Department of Wood Science, University of British Columbia, 2943-2424 Main Mall, Vancouver, British Columbia, Canada V6T-1Z4

[b] Industrial Engineering Research Group, Department of Wood Science, University of British Columbia, 2931-2424 Main Mall, Vancouver, British Columbia, Canada V6T-1Z4

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ABSTRACT

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

* Corresponding author.
E-mail addresses: kmalladi@alumni.ubc.ca (K.T. Malladi), taraneh.sowlati@ubc.ca (T. Sowlati).

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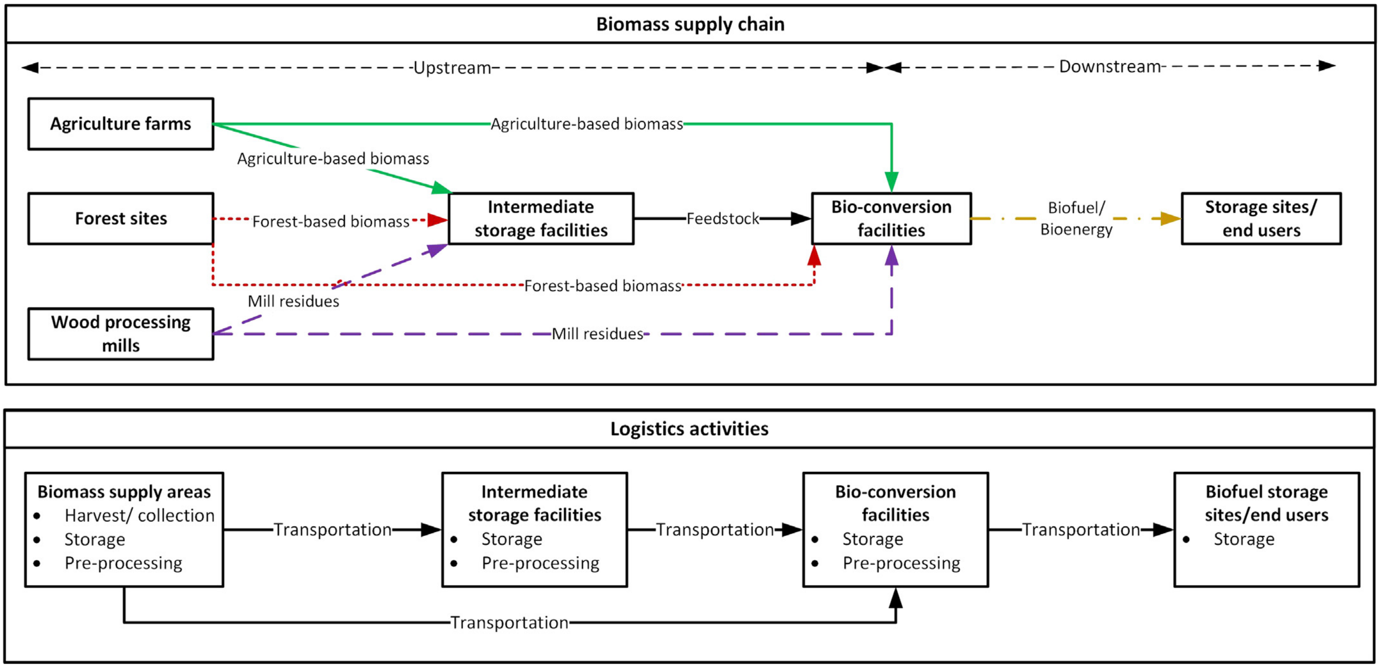

Fig. 1. Biomass supply chain and logistics activities.

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.