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# A review and future directions in techno-economic modeling and optimization of upstream forest biomass to bio-oil supply chains

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ABSTRACT

Recent interest in biomass supply chain management has stimulated research efforts in the industry and academic communities. Techno-economic modeling and optimization efforts targeted on the upstream segment of the forest biomass to bio-oil supply chain are reviewed. Key components of upstream supply chain decision making are then presented through an overview and classification of the existing methods and contributions. There is a need to classify and analyze the relevant methodologies and approaches identified in prior studies, and to subsequently assess their usefulness through empirical research and case-based analysis. Both narrative and systematic literature reviews are performed using qualitative analysis and classic bibliometric techniques to demonstrate the scope of current papers and the call for future needs. It is found, due to growing demands for bioenergy, future biomass-to-bioenergy supply chains should draw upon existing research toward the development of efficient and effective forest biomass supply chain networks. It is further concluded that a new generation of pretreatment technologies is needed for techno-economic optimization of upstream forest biomass value chains.



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## 1. Introduction

### 1.1. Motivation

Since the early 1970s, when the world had its first energy shortage crisis and recognized a looming environmental crisis, interest in developing new sources of energy has risen significantly [1]. A spike in oil prices (2007–2008) created a more recent wave of interest in renewable energy sources [2]. In the United States (U.S.), federal laws, such as the Energy Independence and Security Act of 2007, as well as state level renewable energy standards support greater use of biomass to produce energy [3]. Both industry and academic communities have sought substitutions for fossil-based energy sources. In the 1990s, renewable energy resources, including biomass, hydroelectric, geothermal, solar, and wind, were introduced as novel replacements for fossil-based energy resources (e.g., coal and crude oil) [4]. The growing number of investigations reported in peer-reviewed proceedings and archival journals, as well as online discussions dedicated to the topic, confirms global interest in and support of renewable energy sources (e.g., biogas and biofuels) [5–7]. According to the U.S. Department of Energy [8], 10% of energy in the U.S. is derived from renewable energy sources. Biomass, a renewable and biodegradable energy resource, provides 50% of renewable energy needs in the U.S.; consequently, biomass plays a key role in the energy industry.

Biofuels represent a promising substitute for conventional fuels for mobility and heating applications; however, availability, quality, and variability of biomass greatly affect energy self-sufficiency [9]. Additionally, recent awareness among the internal and external stakeholders over the need to alleviate the level of greenhouse gas (GHG) emissions has motivated research efforts in logistics and management of biomass supply chains (SCs) [10–12]. As witnessed over the past several years with the development of new fossil energy sources (oil sands and shale), high volatility of energy prices is another concern, and is a manifestation of phenomena resulting from constantly increasing demand for a limited supply of fossil energy resources. In spite of its environmental benefits, forest biomass is too costly to compete with fossil fuels in many countries [13,14]. Lower fossil fuel prices would further impair the competitiveness of bioenergy. With the recent price volatility and energy slump, it is prudent to systematically design and optimize the upstream segment of biomass-to-bioenergy SCs. Such efforts directly affect the sustainability and robustness of other activities in the entire value chain [15–17].

### 1.2. Challenges

Increasing bioenergy availability is crucial due to its significant advantages (e.g., reduction of dependence on imported energy and GHG emissions). Supply challenges, (e.g., low energy density and bulky), are major barriers that prevent using forest biomass to produce bioenergy [18]. Botard et al. [2] suggested that wood product market prices and harvest costs are key factors in determining the feasibility of woody biomass utilization. Market prices for competing products, such as wood pulp, can affect biomass availability. Yemshanov et al. [19] observed that biomass supply costs are the biggest constraint to widespread use of forest harvest residues for bioenergy commercialization. Most investigations into biomass processing and bioenergy production focus on the economic aspect [20].

The economic aspect is influenced by several factors. First, biomass has the low-energy density, which results in higher costs for transport and delivery to refinery facilities [20,21]. Second, biomass feedstocks are dispersed and, thus, collection of significant amounts requires traversing large areas [22]. Third, biomass requires pretreatment (e.g., drying and pyrolysis) to reduce moisture content and to enhance its energy density [23,24], which increases production time and cost. Fourth, the seasonal nature and annual variability of biomass require careful planning and scheduling to ensure adequate quality and quantities of the biomass feedstocks [25]. Therefore, design and optimization of the SC network are key challenges of economically feasible conversion of biomass to bioenergy [26].

Several optimization studies have focused on the development of decision support systems for forest biomass SCs [27–29]. Most of these studies have considered economic performance [30–32] through modeling, planning, and management of the value chains. Techno-economic analysis and optimization can help decision makers to deal with a wide range of decision levels (i.e., operational, tactical, strategic). Parker et al. [33] developed an mixed integer linear programming (MILP) optimization model to assess potential biofuel supply across the western U.S.; they explored spatial information, including different feedstocks, potential refinery locations, and transportation networks to maximize the profit in biofuel SCs. Gold and Seuring [34] discussed the principal issues of SCs and logistics for bioenergy production identified by the existing literature. Various review studies report criteria, modeling approach, assumptions, restrictions, uncertainties, and future work to design a proper biomass-to-bioenergy SC structure [17,35–37].

### 1.3. Background

Lignocellulosic biomass is the most abundant type of biomass, and is composed of lignin (15–20%), hemicellulose (25–35%), and cellulose (40–50%) [38]. In addition to its abundance, lignocellulosic biomass (e.g., western juniper in central Oregon, USA) is preferable for several other reasons: the possibility of using non-edible biomass, the ability to obtain a higher net energy yield for the production of fuels and chemicals, and the ability to avoid undue land use change [39,40]. Bio-oil from lignocellulosic biomass is a potential source of a number of valuable chemicals. More than 350 products of lignocellulosic pyrolysis have been identified, including tars, acetic acids, alcohols, esters, aromatics, sugars, turpentine, and methanol [38]. Therefore, investigation into the development of low-cost separation techniques is needed to enable commercialization of these chemicals [38]. Radlein [41] reported a detailed review on the production of chemicals from bio-oils. The commercial competitiveness of bio-oil depends on logistics factors (e.g., availability and industrial practices), the scale and location of bio-refineries, and other factors [42,43].

Various aspects of the upstream segment of biomass to bioenergy SC have previously been discussed [6], and it is essential to develop efficient technologies to assist stakeholders to overcome the identified challenges [13,35,44]. Second-generation conversion technologies, which use nonfood crops such as forest biomass (roots, stumps, bark, leaves, small stems, and branches of live and dead trees) are currently under development, but exhibit unclear technical and economic performance [20,34]. Researchers continue to evaluate the advantages of conversion technologies in terms of energy efficiency [45]. Additionally, several researchers argued and underlined that conversion technology and pretreatment technique (e.g., size reduction and drying) developments can mitigate SC management and logistics issues of biomass to bio-oil SC networks [17,46,47]. Fast pyrolysis process represents a conversion technology for local deployment and is economically attractive for small-scale bio-oil production from lignocellulosic biomass [34,48,49].

Bals et al. [50] reported that the fast pyrolysis process is nearly energy neutral, and that the major costs are capital costs and costs of drying the forest biomass. They reported that the total energy demand during fast pyrolysis is 1.83 MJ/kg; the estimated selling price of bio-oil and bio-char are about \$176/Mg and \$61/Mg, respectively. Upgrading the bio-oil to renewable transport fuel requires a post-conversion, full deoxygenation process through hydrotreating and catalytic vapor cracking. Currently, the high production costs are not competitive with fossil fuel production costs. Another alternative, the production of hydrogen from biomass through pyrolysis, has been extensively investigated [51], since hydrogen and $CO_2$ can be efficiently produced from the water-soluble fraction of bio-oil [52]. Czernik et al. [53] reported that 1.3 Gt/year of biomass can produce 100 Mt/year of hydrogen.

Bio-oil is a low-grade liquid fuel that can be used in industrial heating (e.g., fueling heaters, furnaces, and boilers), industrial turbines, stationary dual-fuel diesel engines, and upgrading to transport fuels [54,55]. Additionally, it can serve as a source of several chemicals and bio-refining feedstock [56,57]. Bio-oil has limitations, however, such as low energy density and corrosive properties that are harmful to existing engines [58]. The high post-conversion processing cost is an essential issue to be considered in producing higher-quality hydrocarbon fuel from bio-oil. The physical properties of bio-oil such as low heating value (half of conventional fuel oil), poor volatility, solids content, high viscosity, coking, corrosiveness, and incompatibility with conventional fuels limit the range of bio-oil applications [54]. Standard bio-oil properties are necessary for commercial application. In order to realize industrial advancements and commercialization of bio-oil-based fuels and chemicals, considerable work is required to overcome the techno-economic challenges of SC logistics, bio-oil production, handling, and upgrading.

Bio-char is another product of the pyrolysis process, which is a valuable fuel for industrial application since it has a high energy content (about 30 GJ/ton) [59]. Bio-char is also used as a soil amendment to improve soil health [60]. Qian et al. [61] reported that the effective utilization of bio-char through thermochemical techniques can improve the economic viability and environmental benefits of biomass. The main applications of biochar include catalysts (for syngas cleaning and synthesis process) [62], soil amendment (for improvement of productivity and soil health) [60], fuel for fuel cells [63], sorbent of contaminant for mitigation of environmental issues [64], gas storage for $CO_2$ and $H_2$ [65], activated carbon for reduction of hydrophobic contaminants [66]. Qian et al. [61] provided an overview of bio-char structure and properties, production methods, and other applications.

In addition to developing cost-effective production technology, an optimal and robust bioenergy system is essential to support a competitive biomass-based energy market [67]. The large number of studies in the field of biomass-to-bioenergy SC that present quantitative assessments indicate the importance of such methods (e.g., cost calculation, geographic information systems (GIS), simulation, and optimization) to overcome the barriers that inhibit the development of the bioenergy sector [6]. More detailed information about the applied quantitative methods and models to evaluate biomass supply chain performance has been previously reported by Ba et al. [68]. The cost calculation method is the simplest approach, and involves summing partial costs of different entities of the SC using spreadsheets for automating calculation. GIS plays an important role as an effective tool and a spatial database that can provide inputs related to biomass availability, biomass logistics, and biofuel facility location selection for spatial and temporal optimization models, however, GIS is not capable of directly optimizing an objective function [68,69]. Simulation methods are more appropriate than the cost calculation and GIS-based methods due to high modeling flexibility and ease of understanding/modifying the model. In addition, the broad choice of simulation software can ease decision making. In spite of the benefits, supply chain simulation modeling is not appropriate for calculating optimal cost, nor for strategic and tactical decisions. Thus, mathematical modeling and operations research approaches (e.g., deterministic, stochastic, and multi-objective optimization) are commonly used to incorporate various decision levels (especially strategic and tactical) into models (e.g., to optimize profit, cost, GHG emissions, and energy consumption) and to facilitate the search for a desired solution [70].

Mathematical optimization has been widely applied over the last decade to address economic objectives in the upstream segment of biomass-to-bioenergy SCs [6,17]. These studies have enabled identification of high yield resources, transportation configurations, coordination of entities (e.g., collection, grinding, delivery, and storage), and efficient technologies. Mathematical optimization models are represented by objective functions (e.g., linear or nonlinear), decision variables (e.g., binary, integer, and continuous), constraints (e.g., capacity, conservation flow, and resource availability), and other parameters [35]. Such models can be used to find the optimal locations and transport pathways with the assistance of binary variables in biomass-to-bioenergy SCs. Deterministic models represent the vast majority of mathematical optimization objectives (e.g., minimizing cost or maximizing profit) in biomass logistics. Stochastic models are less common due to challenges in incorporating uncertainties (e.g., difficulty in developing computational algorithms). Few studies have applied multi-objective models for biomass supply chain optimization due to the complexity of simultaneously handling several objectives (e.g., economic, environmental, and social). Further discussion of stochastic and multi-objective modeling are provided by Awudu and Zhang [36] and Cambero and Sowlati [35]. In particular, mathematical optimization has been demonstrated as a viable approach to aid techno-economic analysis, as discussed in greater detail in the narrative review (Section 3.2).

### *1.4. Objective*

Biomass SC optimization approaches that incorporate various decision levels (i.e., strategic, tactical, and operational) to evaluate sustainability performance have not been found in the literature that integrate conversion processes with the forest biomass SC. Thus, the specific objective of this study is to investigate the nature of the current state-of-the-science and to identify potential future directions for cost effective development of conversion technology for biomass-to-bioenergy SCs. The presented study analyzes and compares distributed and centralized processing network systems that process forest biomass into bio-oil. This study helped to define the topics explored in the literature review. The literature review was conducted using the narrative and systematic techniques and analytical and empirical methods to explore existing research methodologies and approaches. Additionally, this study identifies challenges and benefits of forest biomass supply, as well as simultaneous internal and external stakeholder needs.

## 2. Review methodology

The methodology applied in this literature review addresses the existing methods with respect to the state-of-science and consists of two parts. First, a narrative literature review was conducted by analyzing the contents of publications in the upstream segment of biomass to bioenergy SCs, along with techno-economic modeling appearing over the past four decades. Second, a systematic literature review was conducted using quantitative and qualitative methods for publications appearing from January 1, 2000 to June 30, 2015.

### 2.1. Narrative literature review method

The narrative literature review method identifies the purpose of the research, explores key concepts, and defines chronological advancements in reported research. Narrative review addresses the challenges from the existing articles and proposes solutions to overcome some of the challenges. Herein, it identifies the evolution of research in the upstream segment of the biomass to bioenergy SC, with a focus on technical and economic aspects. The current challenges in forest biomass and bioenergy SC management are identified through the basic concepts, major work, and key contributions. Several studies reported that the upstream (e.g., harvesting, extraction, and transportation) forest fuel SC is influential on the economic viability of biomass to bioenergy SC [71–73].

The conventional structure of biomass to bioenergy upstream SCs includes harvesting and collection, logistics, and storage. In the earlier studies, undertaken using the conventional upstream segment structure, researchers have not considered pretreatment [18,71,72]. Fig. 1a represents the conventional structure of the upstream segment of biomass-to-bioenergy SCs. Several studies [74–76] illustrated the current technology and economic development related to the upstream biomass feedstock SC (e.g., pulpwood and wood residues); these compared the "State of Technology" in 2014 (current state) and 2017 (target design case). Fig. 1b shows the proposed structure, which is composed of four main processes: harvesting and collection, logistics, pretreatment, and storage. Pretreatment can convert biomass to intermediate bioproducts such as bio-oil and bio-char. The pretreatment process is still insufficiently robust to accommodate technology modeling, optimization, and sustainability aspects of biomass to bio-oil SC implementation [17,47].

### 2.2. Systematic literature review method

Since scholars have limited time to keep up-to-date in broad technological research and development, review studies play a key role in bridging science and engineering research. The systematic review (SR) method presents a series of evaluations, strategies, and analyses that assist in identifying key characteristics of previous studies and designing future studies. One of the main features of SR is reduction of author bias in comparison with narrative reviews, which often support the authors' point of view. Thus, complementary systematic and narrative reviews were performed herein to analyze the publications, citations, and adopted research methods in the upstream biomass-to-bioenergy SC domain. These techniques have been previously applied for performing literature reviews in sustainable SC management [77,78]. No prior studies in the bioenergy SC domain have been identified that perform a SR. Thus, quantitative and qualitative methods were developed in the SR applied herein for analyzing recent publication related to biomass-to-bioenergy upstream SC management. The quantitative method presents an analysis of publication data, citation data, and keywords to provide a novel classification for available studies. Fig. 2 summarizes the dimensions of publication and citation data analysis used herein as a quantitative method.

The qualitative method provides a comprehensive characterization of current literature for classifying the research methodologies. Wacker [79] categorized qualitative literature review methods in two main categories (analytical and empirical) and six subcategories. Several studies have used and modified Wacker's classification by identifying additional subcategories [80–82]. Fig. 3 presents the identified categories and subcategories that were used in the qualitative method herein.

## 3. Narrative literature review

The narrative review conducted herein identifies the qualitative evidence of the need for research to improve upstream forest biomass-to-bioenergy system performance and related

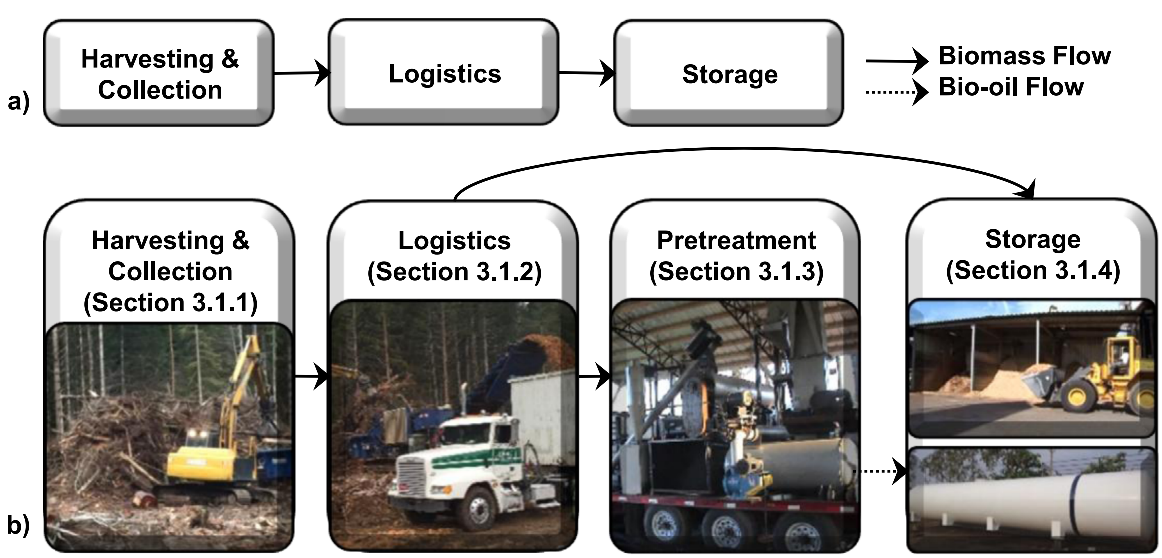


**Fig. 1.** Upstream segment of the general biomass-to-bioenergy supply chain: (a) conventional structure and (b) proposed structure (paper sections are also indicated).

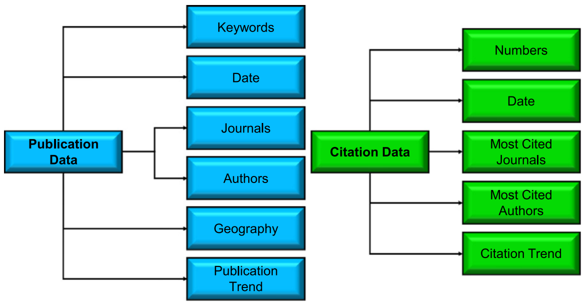


**Fig. 2.** Classification framework for quantitative method [78].

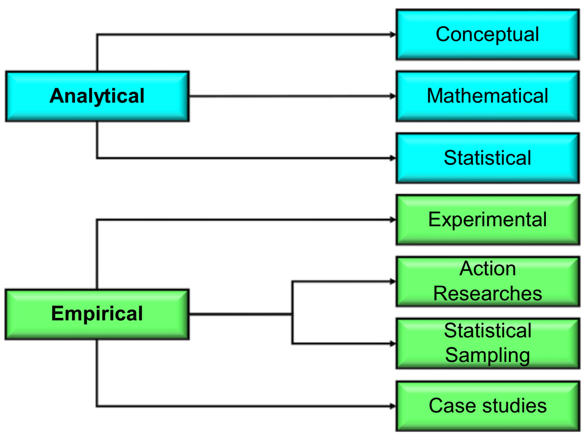


**Fig. 3.** Classification framework for qualitative method [78].

mathematical modeling approaches. Biomass can be classified as lignocellulose (e.g., wood), triglycerides (e.g., vegetable oil), amorphous sugars (e.g., glucose), and starch (e.g., corn). Lignocellulosic biomass is the most abundant, cheapest, and fast-growing type [83,84]. The forest industry is one of the main suppliers of lignocellulosic feedstocks [85].

Forest biomass could support the mitigation of anthropogenic carbon emissions as a renewable energy source and could help forest communities generate jobs and develop local energy sources [35,86]. Forest biomass can be converted to the different fuel types (e.g., solid, liquid, and gaseous) that has higher bulk density [13,87], but energy generation through forest biomass is confronted by several challenges. Some of the main barriers of using forest biomass as an energy resource are high moisture content, low energy density, seasonal variation, conversion technology limitations, and storage space requirements [16,88]. The upstream forest SC is responsible for biomass harvesting and collection, logistics, pretreatment, and storage, as described in the following sections.

### 3.1. Upstream supply chain dimension

#### 3.1.1. Harvesting and collection

Harvesting and collection involves several operations, such as felling, bundling, skidding or forwarding, unloading at landing, grinding or chipping, and loading for truck transport. Harvesting and collection (Fig. 4a and b) of forest biomass is a key step in bioenergy production because it will determine the modes of transportation and storage. Harvesting and collection systems for forest harvest residue (FHR) increased rapidly in the mid-1980s [89] to reduce fire risks, prevent smoke pollution, and create renewable energy sources [26].

Harvesting and collection are highly influential in defining SC cost effectiveness [90]. Harvesting and collection operations can either be coupled or de-coupled. On steeper terrain, harvesting of merchantable logs and biomass is done simultaneously because it is cost prohibitive to return for branches and tops. On flatter terrain, tops and branches left in the field dry more quickly than piled forest residues.

Forest residue availability may be limited by the season or extreme weather, safety, environmental aspects, or site accessibility [2]. Further, the harvest season and operation time can affect biomass yield and energy density [37]. Additionally, increasing the demand for forest biomass coupled with inappropriate harvesting methods have had negative impacts on biodiversity, soil, and water conservation [91]. Spinelli et al. [92] noted that possible alternative methods to employ in forest fuel logistics are transporting loose residue, chipping, or bundling (at collection sites). Hauling loose residue is preferable only for short distances. The major advantages of mechanical particle-size reduction (e.g., grinding or chipping) are reducing the heat requirements for conversion (especially thermochemical process such as fast pyrolysis) and increasing biomass bulk density and yields for ease of handling and transport [93–95]. Grinding forest biomass is an energy-intensive, expensive process with a \$26.12 per oven-dry tonne impact range [96]. Bit type, screen size, and knife-edge bits are major parameters during grinding that affect the bulk density and fuel consumption [97]. Sokhansanj et al. [98] reported that the cost of grinding biomass is nearly \$11/MJ, using three grinders for 450 Gg of biomass (500 collection sites with 800 Mg biomass at each site), but costs can vary depending on equipment used and feedstock conditions.


**Fig. 4.** Harvesting and collection of forest biomass: (a) collected biomass and (b) comminution operation.

Early studies explored harvesting operation systems, collection of large quantities of biomass for energy generation, and improvement of profitability through optimal product allocation [99,100]. Later studies examined the cost/benefit tradeoffs of integrated harvesting systems and developed industrial case studies using the integrated methods and approaches, e.g., economic targets and environmental needs [35,101,102]. Zamora-Cristales and Sessions developed a forest residue collection model to estimate the cost of biomass collection, using forwarders and excavator-base loaders [90]. Their results indicate that excavator-based loader alone, is the most cost-effective approach for less than 50 m distance, and two forwarders and one excavator-based loader is usually the most cost-effective approach for beyond 50 m distance, depending upon mobilization costs. They estimated the optimal collection cost between 15 and 350 m are from $7.2 to $27.5 per dry ton. Thus, rational biomass collection is essential to design an optimal biomass supply chain network. Muth et al. [103] developed biomass SCs that use advanced preprocessing strategies for forest thinning to achieve high quality and low cost biomass in bio-refinery. Puttock [104] developed a model to estimate the production costs for seven integrated harvesting systems from six countries (i.e., Canada, United Kingdom, United States, Denmark, Finland, and Sweden). The author concluded that production costs of fuelwood are highly dependent on the type of harvesting and collection system used.

The harvesting approach fundamentally affects the upstream decision making in terms of producing the desired shape, size, quantity, and quality of biomass at the correct time [71]. Grisso et al. [105] noted that the number of annual harvest days has a significant impact on economics of harvesting, collecting, and storing of biomass. The number of harvest machines required and storage capacity required are dependent upon the number of harvest days. Consequently, a shorter harvest period is a critical variable in scheduling of harvest operations that results in reduced capital and operational costs of harvest machines and storage due to a reduced harvest volume. Pan et al. [26] evaluated harvesting cost and productivity of a whole-tree harvesting system to examine the feasibility of using forest biomass for bioenergy production. They argued that tree size is not a significant economic factor in most harvesting and collection operations (e.g., felling, skidding, grinding, and loading). Laitila and Väätäinen [106] and Röser et al. [107] looked at the various forest biomass supply systems for fuel production, and reported that harvesting and chipping at the roadside was the most cost-efficient supply system. Additionally, Zamora-Cristales et al. developed a stochastic simulation model to analyze the economics of mobile chipper and trucks under uncertainty for bioenergy production from forest biomass [108]. They noted road characteristics (e.g., road gradient, surface, width, and horizontal alignment) and processing locations are important factors that affect truck and chipper standing time, and consequently biomass operation costs.

One of the challenges in the utilization of forest biomass for energy is the environmental sustainability of biomass energy [34]. The Scottish Agricultural College, Finland, and Sweden have developed guidelines for biomass harvesting [109]. These guidelines emphasize retention, disposal, redistribution, burning and mulching, as well as management practices for biomass extraction. The long-term effects of harvest operations and forest biomass removal are on soil productivity, water quality, and habitat [110–112]. Achat et al. [113] quantified the overall effects of removing forest biomass, especially harvest residues (branches) on nutrient outputs, biological soil fertility, and tree growth. Although found to be the most cost-efficient in studies by Laitila, Väätäinen, Röser, and others, their study indicated that whole-tree harvesting has negative effects on soil properties and forest ecosystems. Since present forest biomass harvest operation and forest management guidelines are insufficient, it is essential to develop a novel biomass guideline by integrating existing guidelines with new findings to ensure a sustainable SC [114]. Different approaches are required for each type of harvesting system, which results in different types of forest biomass SCs in terms of handling (e.g., sticks or chips), transportation (e.g., truck or rail), and storage (e.g., covered or uncovered). Since the harvesting approach affects other activities in the biomass-to-bioenergy SC, the main objective is promoting sustainability through mitigating economic, environmental, and social concerns.

*3.1.2. Logistics*

Transportation is a main activity linking the individual entities within biomass-to-bioenergy SCs. Transportation costs are assumed to be a major cost driver associated with obtaining biomass [115]. Transportation attributes, including transport mode (e.g., truck, rail, and ship), vehicle capacity, and distance traveled, have a substantial effect on transportation costs [13]. The delivery cost of forest biomass depends on several other factors, such as road type and road conditions (travel speed), type of biomass (bulk density), harvesting methods, and processing operations [116]. For instance, reliable estimation of biomass pile volume allows decision makers to deploy the processing operations appropriately, and develop an efficient SC [117]. Eriksson and Björheden [118] pointed out that optimizing biofuel production for forest biomass essentially means minimizing transportation cost. Thus, forest biomass logistics costs are a key component of the overall cost of forest activities and bioenergy production [119–121].

Forest biomass can be delivered to bioenergy production facilities by truck, rail, and ship. Trucks transport about 90% of forestry products to mills in the U.S. [122]. Searcy et al. [121] reviewed the associated costs of transferring biomass feedstocks by truck, rail, and ship for small- and large-project sizes in detail. Tractor-trailers and fixed trucks are two types of trucks for transporting forest biomass. Tractor-trailers use standard highway road tractors, which are usually about 12,000 to 20,000 lbs. (5.5–9 metric tons). These types of trucks are designed for greater capacity and higher versatility, compared with fixed trucks [120]. Fixed-trucks are usually shorter than a tractor-trailer and designed for tighter areas and high maneuverability, however, they have the lower payload capacity. Additionally, different trailer options are available for hauling forest biomass, including log trailers, container trailers, and chip vans. Log trailers are designed to haul logs or bundled trees with higher payload capacities. Container trailers are designed to hold bulk material using sturdy walls; they have less capacity than log trailers and chip vans. Chip vans (Fig. 5b) are generally enclosed box trailers approximately 8.5 feet (2.62 m) in width, 8.5 feet (2.62 m) in height, and of various lengths (32–53 ft., 9.8–16.1 m) for hauling chipped or ground products. A drop center can add 10% additional volume [123]. Chip vans are considered to be the most cost-efficient mode of forest biomass transport because of higher payload capacity. Spinelli et al. [92] and Johansson et al. [94] reported the costs of different transportation methods and identified the conditions that can make one preferable over the others. In general, bundling is the least-efficient method and transporting loose residue is the cheapest method, when the travel distance is within 24 miles (40 km) [73].

According to the U.S. Department of Transportation [124], legal load limits on highway roads in the U.S. for tractor-trailer are 80,000 lbs. (36.3 metric tons) gross vehicle weight. To operate above the legal limit, special permits must be obtained [125]. The tare weight of a tractor-trailer is between 26,000 and 30,000 lbs. (11.8 and 13.7 metric tons), including six to ten tandem axles. Badger and Fransham [56] reported that chip vans typically haul between 50,000 and 54,000 lbs. (22.7 and 24.5 metric tons) per


**Fig. 5.** Forest biomass supply logistics for energy production: (a) grinding and loading and (b) transportation (chip van).

load in the U.S. Zamora-Cristales and Sessions explored the economic feasibility of using single trailer and double trailers in three U.S. States (i.e., Washington, Oregon, and California) from the grinder at the landing to the bio-refinery [126]. Their results indicate that double trailers can be a promising alternative under limited conditions only in Washington and Oregon due to State transportation regulations. Additionally, the energy value of a trailer vanload for green wood chips is generally between 210 and 270 GJ, but depends heavily on moisture content [123,127]. Thus moisture management is an important part of the biomass SC, both for transportation optimization and, when used for boiler fuel, to improve biomass combustion value [127].

One of the most challenging problems in transportation planning is road network optimization to minimize total transportation cost. As forest biomass has low value and is bulky, road network optimization plays a key role in efficient and cost effective forest fuel supply [128]. Alam et al. [116] developed a road network optimization model to assist woody biomass supply decision-making for sustainable bioenergy production in northwestern Ontario. They sought to provide efficient and effective woody biomass supply logistics for energy production by minimizing transportation time and cost. Berwick et al. [129] developed a software model which estimates the transportation costs by considering different trucks, equipment, and input prices for different trip characteristics and configurations. One application of the proposed model is forest biomass transport. Zamora-Cristales et al. [130] reported truck/machine interaction to be a key variable limiting biomass conversion efficiency. Comminution (a size reduction technique for lignocellulosic biomass feedstocks) and transportation can be decoupled, but the cost advantages depend upon the situation, e.g., available processing options, location (in-forest yard or bioenergy facility), and transportation options [131]. Since forest biomass has a low bulk density [93], processing biomass through chipping, grinding, and shredding can increase the bulk density [120]. However, comminution of forest biomass has a negative effect on durability and longevity during storage. Additionally, to ensure a continuous supply and meet growing demands during winter and spring seasons, it is essential to use covered storage.

Guzmán [132] evaluated the technical and economic feasibility of producing wood chips under different conditions. Guzmán also explored different variables such as working hours and transportation cost to investigate woodchip production in Chile. Processing of forest biomass can increase the bulk density of wood chips and grindings, which is essential to improve handling efficiency. Processing can occur at any step in the upstream forest biomass SC, although it is lower cost when integrated with harvesting and collection [48,71]. Gold and Seuring [34] reported that the most common processing options after harvesting and collection are drying, baling, chipping, and grinding (Fig. 5a). Zamora-Cristales et al. [133] demonstrated that bulk density of dry grindings could be increased more than 20% through vertical blowing into trailers. Kanzian et al. [134] developed a method for forest biomass logistics supply through a combination of geographic information systems (GIS) and linear programming. The results indicated that direct transport of forest biomass and chipping at the destination is the lowest-cost fuelwood SC system. Additionally, biomass can be chipped at or near the harvesting site and transported via chip trucks at a slightly higher cost. The authors argued that harvesting residues can only be recommended for large-scale refineries because of poor quality and low biomass yield. A prior study found that the roll-off approach would improve economic efficiency and forest residue accessibility [135]. Han et al. [136] and Harrill et al. [137] proposed a new approach using a roll-off truck paired with a small skid-steer loader to collect and transport slash to the centralized processing areas for bioenergy production. They applied the proposed approach to quantify the operational costs of removing biomass. Since transportation costs significantly increase with a slight increase in truck travel time and distance [138], the roll-off truck approach is appropriate for short distances. Further studies are essential to explore the application of this approach into forest biomass collection and transportation [136]. Bisson et al. [139] evaluated the use of a modified off-highway dump truck to shuttle residues from roadside piles to a centralized landing where a high capacity grinder loaded trailers pulled by $6 \times 6$ truck tractors to a transfer point. The trailers were then dropped at main roads for pickup by on-highway $6 \times 4$ truck tractors.

Production rates, costs, and fuel consumption rates for various grinding and transport configurations were calculated by Johnson et al. [140] for grinding harvest residues in the inland West United States. For the base conditions of the study, grinding at the landing and transporting ground material in chip vans to the refinery was the lowest cost option, followed by grinding and shuttling to an intermediate access point for loading into a large truck. Shuttling loose material to an intermediate point before grinding was the most costly option. Zamora-Cristales et al. [131] developed an economic optimization model for processing and transporting forest biomass by considering options for comminution at each residue pile, processing in central yards, and processing at the bioenergy refinery using different types of trucks, trailers, and grinders. Forest residues could be ground or bundled. Their software model used a combination of simulation and mixed integer programming to identify the most cost-efficient system.

*3.1.3. Pretreatment*

Pretreatment process is one of the essential steps for further efficient conversion of forest biomass [141]. Since lignocellulose is composed of cellulose, lignin, and hemicellulose, a pretreatment process is required to make these substances accessible for further conversion to be used for the production of energy (e.g., heat, power, and transport fuel), chemicals, or other purposes [142]. There are many pretreatment technology types for forest biomass have been introduced in the literature, including mechanical, chemical, and biological, as well as the various combinations of these technologies [142]. Pretreatment conversion technologies (e.g., thermolysis or pyrolysis processes) for forest biomass impacts the economic, environmental, and social aspects of the bioenergy production system [34]. Thermochemical technologies (e.g., combustion, hydrothermal liquefaction, gasification, and pyrolysis) are one of the most suitable pretreatment conversion processes in terms of simplicity and cost-efficiency to produce heat, electricity, and fuels [38]. The cost of pretreatment varies with the capacity of facilities, the type of conversion technology, and type of biomass. Conversion efficiency and scale of conversion are two key factors that affect economic feasibility of bioenergy production. Wright and Brown [143] provided detailed information about the optimal size of bio-refineries, using different technologies such as gasification or pyrolysis, for different types of biomass. Additionally, to increase production yield and reduce the required heat, biomass required mechanical particle size reduction and drying through thermochemical processes to feeding feedstock into a pyrolysis reactor.

The pyrolysis process, by definition, involves chemical change brought on by heating biomass feedstock in the absence of oxygen [56]. It has been classified into three types, i.e., slow, intermediate, and fast pyrolysis, based on the length of reaction time [17]. In this review, the terms fast pyrolysis and pyrolysis are used interchangeably. Pyrolysis oil, or bio-oil, is produced from biomass feedstock mainly through fast pyrolysis processes that condense a mixture of oxygenated hydrocarbons and water [144]. The characteristics of the fast pyrolysis process include very high heating rates, reaction temperatures of around 500 °C (932 °F) in the vapor phase, short vapor residence times (typically less than 2 s), and rapid cooling of the vapors to produce bio-oil [56]. The fast pyrolysis process decomposes the biomass to char, light gases, and a vapor phase of oxygenated hydrocarbons and water. Fig. 6 illustrates the general biomass pyrolysis conversion and upgrading process as a post-conversion process. Bio-oil can be upgraded to biofuels through hydrotreating and hydrocracking processes to break down long-chain hydrocarbons and reduce oxygen content [17,84,145]. Several parameters affect the pyrolysis process, including biomass species, temperature, particle size, feed rate, and residence time of volatiles. Additionally, internal bio-oil consumption, instead of diesel to provide electricity for pyrolysis plant and selling bio-char, can reduce the cost up to 18% [55]. Using bio-char instead of electricity consumption has a significant impact on bio-oil commercialization.

Luo et al. [146] reported that the biomass species and temperature play a significant role in pyrolysis efficiency and effectiveness, and noted the optimal temperature to produce the highest quality bio-oil is about 773 K (500 °C or 932 °F) within roughly one second. The yields of the three main products reported for fast pyrolysis process are 50–75% bio-oil, 15–25% bio-char, and 10–20% syngas (non-condensable gas) [147,148]. More detailed information about the properties of pyrolysis oil from wood have been previously reported [149–151].

Bio-oil is a viscous mixture of oxygenated hydrocarbons and water. Bio-oil has 1200 kg/m$^3$ bulk density, 20–30% water content, a heating value between 16 and 19 MJ/kg, and a product value of about $4.70/GJ [57]. Despite the addressed shortcomings, bio-oils can be upgraded into several chemicals, transportation fuels, and also hydrogen [52,152]. Chattanathan et al. [51] reported the major hydrogen production techniques, including the bio-oil steam reforming technique, and the important factors that are known in hydrogen production (e.g., temperature, catalyst type, and carbon ratio). The cost of production of hydrogen from bio-oil is reported to be $27.42/GJ ($3.25/kg or $0.86/liter) [153]. Czernik and French [154] estimated the cost of hydrogen production using fast pyrolysis bio-oil at $4.26/kg, of which bio-oil contributed to 56.3% of the production cost.

Fast pyrolysis production technology has developed rapidly since the late 1970s and reached near commercial status in the 1990s [155]. Czernik and Bridgwater [156] argued that the fast pyrolysis process has met commercialization targets for chemical products; and is being developed for producing liquid fuels. Several companies, such as Red Arrow Products Co. (U.S.), DynaMotive (Canada), BTG (The Netherlands), and Fortum (Finland), constructed different types of fast pyrolysis facilities, e.g., circulating fluidized bed and bubbling fluidized bed technologies, with different capacities ranging from 10 to 100 t/day. Fast pyrolysis is currently the only simple, profitable, and efficient route for lignocellulosic biomass [54,84], and has average annual return on investment of 3.5% [50]. The high uncertainty in the selling price of bio-char and bio-oil, however, reduces the viability of pyrolysis on a regional scale [50]. The capital and operating costs of fast pyrolysis refineries were estimated to be about $48.3 million and $9.6 million, respectively, to convert 550 dry tons/day of forest chips to 426 t/day of bio-oil [145]. Venderbosch et al. [157] discussed the principles, the main conversion technologies, and the economic viability of fast pyrolysis processes. They also reviewed bio-oil applications and technology development for production of biofuels and chemicals from bio-oil. Pu et al. [158] examined the major chemical constituents of lignocellulosic biomass and reviewed the recent advances in the conversion of biomass to biofuels. Ringer et al. [145] reported bio-oil production cost, selling price, and some applicable attributes of bio-oil from various reports. Rogers and Brammer [159] compared the selling price of

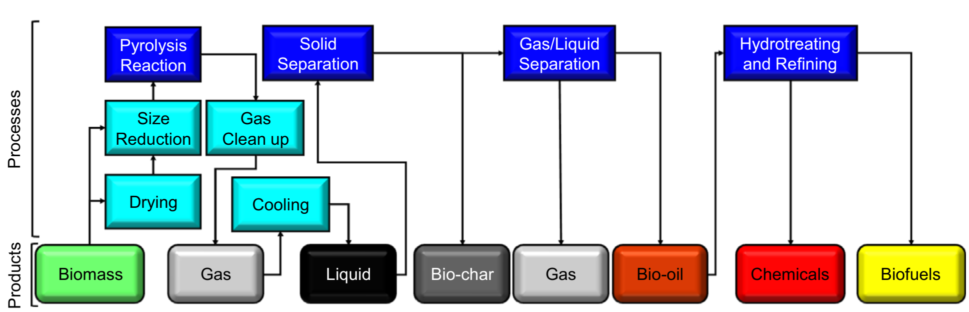


**Fig. 6.** General biomass pyrolysis conversion and post-conversion processing [38].

**Table 1**
Previously reported bio-oil production costs.

| Study | Bio-oil cost | | Refinery size (metric ton/day) | Year |
|---|---|---|---|---|
| | $/gal | $/GJ | | |
| Solantausta et al. [160] | 0.59 | 7.30 | 1000 | 1992 |
| Cottam and Bridgwater [161] | 0.41 | 5.00 | 1000 | 1994 |
| Gregoire and Bain [162] | 0.50 | 6.10 | 1000 | 1994 |
| Islam and Ani [163] | 1.73 | 21.20 | 2.4 | 2000 |
| Islam and Ani [163] | 0.82 | 10.10 | 24 | 2000 |
| Mullaney et al. [147] | 1.21 | 14.50 | 100 | 2002 |
| Mullaney et al. [147] | 0.89 | 10.60 | 400 | 2002 |
| Peacocke et al. [164] | 0.77 | 9.50 | 48-Wellman | 2004 |
| Peacocke et al. [164] | 0.65 | 8.00 | 48-BTG | 2004 |
| Marker [165] | 0.43 | 5.10 | 2000 | 2005 |
| Marker [165] | 0.55 | 6.77 | 500 | 2005 |
| Ringer et al. [145] | 0.62 | 7.62 | 550 | 2006 |
| Uslu et al. [45] | 0.67 | 6.00 | 132 | 2008 |
| Van de Velden et al. [59] | €0.70-€0.73 | €8.70-€9.30 | – | 2008 |
| Dynamotive [166] | 0.74 | 4.04 | 200 | 2009 |
| Badger et al. [148] | 0.94 | 11.54 | 100 | 2010 |
| Czernik et al. [53] | 0.48 | 6.00 | – | 2010 |
| Wright et al. [95] | 0.83 | 10.19 | 2000 | 2010 |
| Rogers and Brammer [159] | £0.733 | £9.00 | 400 | 2012 |
| Jones and Male [167] | 0.59 | 7.24 | 2000 | 2012 |
| Brown et al. [168] | 1.76 | 21.73 | 5 – 15 odt[1] | 2013 |
| Czernik and French [154] | 0.78 ($76/ton) | 9.57 | – | 2014 |
| Mirkouei et al. [29] | 1.15 | 14.11 | 13.6 | 2015 |
| Mirkouei et al. [27] | 1.10 | 13.5 | 50 | 2016 |
| U.S. EIA [169] (Fuel Oil No. 6)[2] | 0.31 | 2.09 | N/A | 1992 |
| U.S. EIA [169] (Fuel Oil No. 6) | 0.99 | 6.26 | N/A | 2015 |

Assumes 4.55 kg/gal (1.2 kg/liter) density of bio-oil and 17.9 MJ/kg high heat value of bio-oil; [1]odt = oven dry ton; [2]157.9 MJ/gal high heat value of fuel oil No. 6.

bio-oil with gas oil and heavy fuel oil produced using different refinery sizes. Table 1 presents estimated bio-oil production costs as reported in the literature for different refinery sizes.

Fast pyrolysis concentrates forest biomass energy content into a smaller volume, which facilitates storage and transport [157,170]. Converting bio-oil to biofuels further increases the energy density of biomass, and reduces the high oxygen content (deoxygenation) and the formation C-C bonds. Deoxygenation of biomass, which can be accomplished via elimination of $H_2O$ and/or $CO_2$, is crucial since oxygen reduces the heat content and inhibits blending of fuels [171]. Advantages of pyrolysis as a pretreatment technology include easier, less costly handling, higher bulk density, and removal of char [172,173]. Bio-oil has an energy density of six times that of green forest biomass at 45% moisture content [56]. Bradley [174] reported the advantages of bio-oil compared to crude oil, e.g., its tendency to separate and sink when spilled in water. Bio-oil properties and process yield depend on biomass feedstock type, product collection methods, and conversion process type (e.g., rapid heating and cooling, reaction temperature, heat transfer rate, and residence time [58]), among other factors. Table 2 presents the attributes for several types of biomass and bio-oil, based on a study by Badger and Fransham [56].

Current state-of-the-art and next generation conversion technologies, and their attributes for bio-oil production are shown in Table 3. Fast pyrolysis has been the focus for the past 15 years, and is the focus of this literature review, because other technologies have either been in early development or are too costly. For instance, hydrothermal liquefaction is an alternative to fast pyrolysis for bio-oil production, but is more expensive since it requires higher pressures and longer residence times and uses high

**Table 2**
Attributes of several types of biomass and bio-oil [56].

| | Density ($kg/m^3$) | MC (% wb) | Energy Density | | EDR |
|---|---|---|---|---|---|
| | | | MJ/kg[1] | $GJ/m^3$ | |
| **Green whole tree chips** | 350 | 45 | 10.7 | 3.7 | 1/6 |
| **Solid wood, low density (Douglas-fir)** | 400 | 12 | 17.1 | 6.8 | 1/3 |
| **Solid wood, high density (Oak)** | 865 | 12 | 17.1 | 14.7 | 2/3 |
| **Bio-oil** | 1200 | – | 18.0 | 21.6 | 1 |

MC %wb: Moisture content on a percentage wet basis.
EDR: Energy density ratio of bio-oil to other forms of biomass.

**Table 3**
Current and future generation bio-oil production technologies [175, 176].

| Technology | | Temperature (°C) | Pressure (MPa) |
|---|---|---|---|
| **Current** | Fast pyrolysis | ~500 °C | 0.1 |
| | Bio-oil stabilization | 150–250 | 10 |
| | Hydroprocessing | 300–350 | 20 |
| **Under development** | Catalytic fast pyrolysis | ~500 | 0.1 |
| | Hydrothermal liquefaction | ~375 | ~20 |
| | Hydropyrolysis | ~375 | 1–5 |

moisture feedstocks such as animal manure. However, the process produces a lower oxygen content bio-oil, has a higher process yield, and requires less additional processing than pyrolysis [175].

Several organizations, such as Renewable Oil International (ROI) LLC [177], have developed technologies to convert biomass-based renewable resources to liquid or gas products through different intermediate technologies. Fig. 7 shows a first-generation mobile pyrolysis refinery (trailer-mounted units) built by ROI in 2003. Larger units would incorporate two or more smaller units hooked together. Badger and Fransham [56] discussed some of the broad applications of mobile bio-refineries, e.g., locating in close proximity to biomass resources and transportation of high energy density product (bio-oil) instead of low energy density product (forest biomass) to centralized facilities, which would, consequently, reduce handling, transportation, and storage costs to roughly half for bio-oil, compared to biomass feedstock in the form of chips.

**Fig. 7.** A mobile fast pyrolysis bio-refinery (Courtesy of Phillip C. Badger, Renewable Oil International LLC).

### 3.1.4. Storage

Capital and operational costs of storage facilities lead to higher logistics costs [134], thus a key challenge in forest biomass logistics is storage, especially in winter and spring seasons. This problem has received little attention in biomass fuel SC research, however, and researchers usually ignore the effects of biomass storage on the overall SC cost [178]. Various types of storage for biomass resources and associated material losses have been reported [17,178,179]. Rentizelas et al. [178] evaluated three methods frequently used for biomass storage and applied them in a case study to compare the overall cost and material loss rate. In the first method, the storage facility is attached to bio-refinery and uses hot air generated by the refinery to reduce moisture content and avoid quality degradation of the biomass. In the second method, a covered, metal-roofed storage facility is used without biomass drying. Finally, an ambient storage method was considered, which involved covering the biomass with a plastic film. The positive effect of using the first method depends on the biomass moisture level; forest biomass typically has a moisture content of at least 50–60% (wet basis), immediately post-harvest, and varies depending on the season. Additionally, since the storage space required for biomass feedstock is determined by the amount of biomass inventory, minimizing holding inventory is essential to reducing storage costs and develop an effective SC network. Rigdon et al. [180] evaluated the effect of various storage conditions on biomass constituents (e.g., cellulose, hemicellulose, and lignin). Their results indicated a dramatic decrease in ethanol production from 0.2 to 0.02 g/L when using uncovered storage over six-month period, while ethanol yields remained relatively stable when using covered storage. Therefore, covering biomass during storage is essential for maintaining high biofuel yields, especially for ethanol production. In addition to degradation (1% material loss/month), the common lowest cost option, ambient (uncovered) storage, also raises potential health risks, mainly due to high water content [178]. Covered storage has a higher cost, but lower biomass degradation (0.5% material loss/month). A high quality, closed warehouse with hot air drying can be used for storage, and exhibits negligible material loss [179].

Generally, an SC storage problem can be developed as a warehouse location problem, where the capital and operational costs of storage are optimized using different approaches. Biomass storage facilities (Fig. 8a) are often located near harvesting sites or bio-refinery sites. Some studies have considered siting intermediate storage facilities between harvesting sites and bio-refineries [181,182]. An intermediate storage facility can increase overall cost due to the additional handling and transportation. Studies have explored siting the storage facility adjacent to the bio-refinery [183]. Reducing biomass moisture content prevents potential safety and health issues, thus one of the major advantages of co-locating storage and the bio-refinery is the ability to dry biomass using waste process heat. Pettersson and Nordfjell [184] examined the fuel quality of logging residues by considering moisture content, dry matter losses, ash content, and calorific value, before and after storage and handling. Murphy et al. [185] developed a model for predicting the moisture and energy content of forest biomass over a 16-month period in Ireland. They pointed out that the key factors affecting biomass moisture content change are biomass type, storage type, and evapotranspiration. Larson et al. [186] analyzed the potential impacts of biomass feedstock storage losses on inventory management and plant-gate cost in east Tennessee. They found that last-in, first-out biomass feedstock inventory management can minimize the plant-gate cost. They also argued that harvesting time and location are two key factors influencing inventory and delivery management.

Drums, barrels, tanks, and similar containers can be used to store bio-oil. The two main approaches to store pyrolysis oils are underground storage tanks and external storage tanks (Fig. 8b). Decision makers need to consider various aspects in selecting an appropriate storage facility, including the mass/volume of substances. Existing complexity and properties of pyrolysis oil (e.g., corrosivity, instability, and high acidity) lead to limitations in storing this product. Biomass pyrolysis oils contain reactive organic compounds that can change the physical properties and increase the molecular weight of the oil during storage [187]. Since pyrolysis oils are corrosive to common storage tank materials (e.g., steel), further investigation is required to mitigate reactions between the oils and the tank materials [188]. Yang et al. [54] reported the recent developments in storing bio-oil, using different methods (e.g., physical and chemical) that can improve bio-oil properties.

Czernik [188] proposed a method that can be used to predict the effects of various storage conditions on pyrolysis oil properties. He also evaluated the impacts of different storage conditions on physical and chemical properties of pyrolysis oil from woody biomass using three storage temperatures: 37, 60, and 90 °C (98.6, 140, and 194 °F, respectively) over different periods of time. He used oils generated using the vortex reactor system at the National Renewable Energy Laboratory (NREL). The results indicated that pH remained constant during storage, while molecular weight, water content, and viscosity increased with storage temperature and time. Czernik also evaluated polyester resin and high-density polyethylene materials for chemical resistance to pyrolysis oils at 20 and 60 °C (68 and 140 °F). The results indicated that both would be suitable materials for construction of pyrolysis oil storage tanks; each only exhibited slight swelling (less than standard). Prior to Aubin and Roy [189] and Soltes et al. [190] reported that wood pyrolysis oils can destroy and corrode aluminum and carbon steel at even moderate temperatures. For best performance, pyrolysis oils should be stored in air-free stainless steel and/or polymer tanks at room temperature.

### 3.2. Techno-economic modeling

Techno-economic assessment has been used by investigators to explore and couple the technical and economics standpoints of the processes involved in bioenergy production from lignocellulosic biomass that represent the largest portion (~60%) of the total SC costs [141]. Techno-economic assessment can define the potential


**Fig. 8.** Renewable energy storage solutions using a) biomass (chips) and b) bio-oil (pyrolysis oil).

methods as it depends on several factors, such as, biomass type and desired products, as well as the process objectives (e.g., economic assessment or environmental impacts) to determine the economic feasibility [191]. The main purpose of techno-economic modeling is to evaluate investment factors and better define the bottlenecks of process configurations, and consequently to promote the bioenergy yield and reduce capital expenditures [95]. The basic techno-economic modeling includes cash flow and rate of return analysis by employing Aspen Plus software for technical modeling (i.e., mass and energy calculations) and Aspen Icarus software for size and equipment costs, along with a spreadsheet investment analysis [95,145]. A risk analysis can be developed to evaluate the maturity of the technology and accuracy of the economic analyses, which the accuracy is usually $\pm 30\%$ of the actual cost [191]. The total plant investment cost includes following major costs: project investment, fixed operating cost, and variable operating cost, as well as overhead and contingency factors to total installed equipment cost. Swanson et al. [191] reported the general techno-economic model assumptions for biofuels production, including assumption of financial, capital costs, operating costs, feedstock and products, process, and miscellaneous in detail.

Based on the existing techno-economic analysis, pyrolysis process has been reported as being potentially cost-effective pretreatment method for production of transportation fuel from lignocellulosic feedstocks [95,192]. Additionally, fast pyrolysis technology has been commercialized, and there are several companies producing bio-oil, such as Eysen in Ontario and Wisconsin, Dynamotive in Vancouver, Advanced Biorefinery Inc. in Ontario, and Renewable Oil International, LLC in Alabama, as well as research laboratories in National Renewable Energy Laboratory in Golden, Colarado, Iowa State University, and University of Oklahoma [193]. There is a wide range of pyrolysis reactors introduced, which comprehensively reviewed by [155,156,194]. The following reactors have been implemented commercially: bubbling fluidized bed, circulating fluidized bed, mechanically mixed beds, rotating cone reactor, vacuum pyrolysis, and ablative pyrolysis [195]. Prior studies reported that post-conversion methods are immature and there are no commercial post-conversion enterprises for producing transport fuel from forest biomass. Wright et al. [95] examined a techno-economic study on fast pyrolysis of biomass to bio-oil, and upgrading to diesel range fuels in two different scenarios: (1) using self-generated hydrogen from bio-oil and (2) purchasing hydrogen for fuel upgrading. The capital costs of establishing these plants are \$287 and \$200 million, respectively [95]. Their process design includes the following eight components: chopping and grinding, drying, pyrolysis, solid removal, bio-oil recovery, storage, combustion, and hydroprocessing. Their results indicate transport fuel production cost in Scenario 1 (when hydrogen is produced from the process itself) is higher. Other bioenergy production pathway, such as biochemical or gasification, can be promising, but it requires further techno-economic analysis to design an efficient platform. The results of prior studies indicate a significant difference in technology choices and development levels due to various assumptions used by each study [191]. Table 4 represents a number of the techno-economic studies use for bio-oil production via pyrolysis of biomass.

Polagye et al. [57] examined the economic feasibility of biofuel and bioenergy production through techno-economic analysis on four types of bio-refineries (i.e., mobile, transportable, stationary, and relocatable) in order to quantify the transportation-production trade-offs. The main characteristics of these bio-refineries are given in Table 5, and other detailed characteristics are provided in their study. Additionally, they provided operational and economic parameters for loading, unloading, chipping, and debarking. Polagye et al. proposed a fast pyrolysis cost chain (annual cost) for different types of facilities. The relocatable bio-refinery can be disassembled and rebuilt to tradeoff between the large production refinery and feedstock availability. Polagye et al. also argued that biofuels production using a mobile or transportable bio-refinery is more costly than using a stationary or relocatable bio-refinery. Biofuel production using a centralized bio-refinery (i.e., stationary and relocatable) is preferred by industry, due to larger capacities that can achieve lower costs in large-scale systems.

## 4. Systematic literature review

A systematic review (SR) was used to identify leading journals and scholars and to assess the trends in biomass-to-bioenergy SC research. This SR evaluated publication data, citations, and keywords in a quantitative manner for recent literature. In addition, the key research methodologies employed by the most-cited articles were classified.

### *4.1. Analysis of publication data*

In this study, the authors used the Web of Science™ (Thomson-Reuters) to gather the titles, abstracts, and keywords for relevant international conference and journal articles between January 1, 2000 and June 30, 2015. These records were collected into two databases using the following sets of keywords in the Web of Science™ queries:

**Keyword Set 1:** (Lignocellulosic OR Forest OR Wood) AND (Biomass OR Biofuel OR Bioenergy) AND Supply Chain.

**Keyword Set 2:** (Forest OR Wood OR Lignocellulosic) AND (BioOil OR Bio-oil OR Pyrolysis Oil) AND (Economic OR Cost OR Supply Chain).

A period of January 1, 2000 to June 30, 2015 is chosen for SR due to the low number of studies in forest biomass to bioenergy SCs before 2000. From 1980 to 1999, only four and eleven records were found from keyword Set 1 and Set 2, respectively. The query for Keyword Set 1 from the Web of Science™ Core Collection (1965-present) generated a database of 277 records related to forest biomass SCs. Using Keyword Set 2, 126 records were identified that were related to forest pyrolysis oil SCs. A comparison of the two databases found nine papers in common. VOSviewer software [208] was applied to analyze the database records. From the SR results for the keyword queries, it can be seen that biomass-to-bio-oil SC research is accelerating, with the most rapid growth occurring over the last 5–7 years (Fig. 9).

Table 6 reports the ten journals with the most records in the databases for both sets of keywords. The top journals in both databases are the International Journal of Biomass and Bioenergy, Renewable Sustainable Energy Reviews, the Journal of Biofuels, Bioproducts & Biorefining (Biofpr), and the Journal of Applied Energy.

Table 7 reports the 10 countries with the highest level of authorship in this field of research. Most publications in both databases are authored by researchers from the United States, Canada, Finland, and England.

Table 8 reports the ten most productive scholars in each research field (database) examined. Taraneh Sowlati (eleven papers) and Amit Kumar (five papers) have the most publications in the forest biomass SC (Keyword Set 1) and bio-oil SC (Keyword Set 2), respectively. Sowlati has an academic background in biomass SC management, mathematical modeling and optimization, life cycle assessment, multi-criteria decision making, and simulation. Kumar has an academic background in energy and environmental modeling, life cycle assessment, and techno-economic assessment of energy systems.

Table 9 presents the ten most productive organizations in forest biomass SC (Keyword Set 1) and bio-oil production (Keyword Set

**Table 4**
Techno-economic studies for bioenergy production via fast pyrolysis (1991–2016).

| Study | Research Overview | Year |
|---|---|---|
| Elliott et al. [196] | A review study on thermochemical conversion of biomass to liquid fuel (pyrolysis and liquefaction) was provided for 1983–1990. Techno-economic assessment results indicated the pyrolytic process was moving quickly forward in development. | 1991 |
| Solantausta et al. [160] | A techno-economic study was conducted to estimate cost of using pyrolysis and liquefaction to produce transportation fuel from woody biomass. The estimated lowest cost for transportation fuel production was $12/GJ and fuel efficiency is around 50%. | 1992 |
| Cottam et al. [161] | A techno-economic assessment was conducted to investigate and compare economic and technical opportunities for upgrading pyrolysis oil to higher quality fuels. | 1993 |
| Gregoire and Bain [162] | A process model was developed for bio-oil production from wood chips to investigate the characteristics and parameters (equipment cost, plant size, and production capacity) of the process to gain insights about techno-economic evaluation and viability of process developments. | 1994 |
| Mitchell et al. [197] | A decision support system was developed to facilitate techno-economic assessment of biomass to bioenergy systems. Economic and technical parameters were assessed for various feedstocks and conversion technologies. The reported results indicate the relation between the delivered feedstock cost and bioenergy cost. | 1995 |
| Östman et al. [198] | A techno-economic assessment and comparison of pelletizing and pyrolysis were reported for wood fuels production. The results illustrate the need for further development is necessary to promote the quality of pyrolysis oil. | 2000 |
| Bridgwater et al. [42] | Techno-economic assessments of thermal processes (combustion, pyrolysis, and gasification) to generate power (dual fuel diesel engines) from wood chips were reported, considering activities from chip transportation to power supply to the grid. It was found a large pyrolysis plant would have lower cost than gasification. | 2002 |
| Mullaney et al. [147] | Techno-economic assessments were conducted for different types of pyrolysis (fluidized bed and circulating fluid beds). It was concluded that the bio-oil industry was immature and had many challenges for commercialization, such as bio-oil quality, plant size, and bio-oil standards. | 2002 |
| Ringer et al. [145] | A study synthesized the relevant issues (technical requirements, bio-oil stability, applications, environmental, and safety) for advancing the pyrolysis technology to commercialization. A techno-economic analysis was conducted on a bio-oil plant, which included feed handling and drying, pyrolysis, combustion, and recovery. | 2006 |
| Polagye et al. [57] | A techno-economic assessment was reported for bio-fuel production from various materials (chips, pellets, bio-oil, and methanol), using different facilities (mobile). The reported results indicate the cost competitive thinning option for transferring beyond 300 km distance are pelletization and fast pyrolysis. | 2007 |
| Uslu et al. [45] | A techno-economic comparison of different pretreatment technologies (torrefaction, pelletization, and fast pyrolysis) was reported; torrefaction was found most promising in terms of cost. Pretreatment technologies were shown to have a significant impact by easing transportation and handling. | 2008 |
| Magalhães et al. [199] | A techno-economic assessment was presented to evaluate three different preconversion processes (rotating cone reactor pyrolysis, fluidized bed reactor pyrolysis, and torrefaction) for bio-oil production from biomass. The results indicate that torrefaction is the most cost-effective option. | 2009 |
| Osamaa et al. [200] | A techno-economic analysis was conducted to compare the bio-oil production from wood and agriculture using fast pyrolysis. It was reported that agricultural residues were more challenging for bioenergy production due to the high amount of alkali metals and nitrogen in the oil. | 2009 |
| Wright et al. [95] | A techno-economic assessment was conducted for transportation fuels production from pyrolysis oil, using two different scenarios: self-produced hydrogen or purchasing the hydrogen. The reported results indicate that fuel cost is almost 30% less when hydrogen is purchased. | 2010 |
| Anex et al. [201] | A techno-economic assessment was used to evaluate three different conversion technologies (pyrolysis, gasification, and biochemical) for liquid fuel production from biomass. The reported results indicate that the fuel from pyrolysis had the lowest cost and biochemical had the highest cost. | 2010 |
| Trippe et al. [202] | A techno-economic analysis was presented to compare eight different pyrolysis configurations to identify promising technology that indicate major cost-drivers, i.e., biomass feedstock and investment costs. The reported results indicate the biosyncrude (bio-oil and biochar) was possible produce in Germany at costs of €35/MWh. | 2010 |
| Badger et al. [148] | A techno-economic analysis was performed to evaluate the bio-oil production, using fast pyrolysis transportable plant with 100 dry ton per day capacity. It was reported the energy cost bio-oil and biochar was valued at $6.35/MMBTU. Also feedstock cost can drastically affect the final bio-oil cost. | 2010 |
| Ghezzaz et al. [203] | A techno-economic comparison between different conversion configurations was performed. The reported results indicate that fast pyrolysis has higher internal return rate, hardwood is the most suitable feedstock for biochemical process, and profitability is dependent on biomass cost and quality. | 2011 |
| Rogers and Brammer [159] | A review study was presented on techno-economic analysis for bio-oil production, as well as a model to evaluate the cost and performance based on the prior scenarios in the literature. The results indicate it is possible to produce bio-oil from biomass with similar costs as distillate fuel oil production in the U.K. | 2012 |
| Brown et al. [204] | A techno-economic analysis was performed for the fast pyrolysis and hydroprocessing pathway to investigate the feasibility of cellulosic biofuels from biomass. It was concluded the minimum fuel selling price of diesel fuel and gasoline produced via fast pyrolysis along with hydroprocessing to be $2.57/gal. | 2013 |
| Brown et al. [168] | A techno-economic analysis was reported for biofuel production using mobile conversion facilities (fast pyrolysis and torrefaction). Results show converting forest residue to more energy dense products (bio-oil and torrefied wood) has lower delivery cost than using conventional wood chip delivery. | 2013 |
| Do et al. [205] | A techno-economic analysis was provided for bio-oil production from empty fruit bunches via fluidized-bed fast pyrolysis. Several factors (capital cost, payback period, and product value) were estimated to evaluate economic feasibility. It was reported that plant size and bio-oil yield are key parameters on the product value. | 2014 |
| Thilakaratne et al. [206] | A techno-economic analysis was performed for biofuel production from microalgae using two different conversion pathways (thermal drying prior to catalytic pyrolysis and mechanical dewatering prior to catalytic pyrolysis). The results show mechanical dewatering has higher energy efficiency than thermal drying. | 2014 |
| Zhao et al. [207] | A techno-economic analysis under uncertainty was conducted for several conversion pathways (gasification, pyrolysis, liquefaction, and fermentation) to investigate economic feasibility of biofuel production. Results show none of the pathways would be profitable, but fast pyrolysis and hydroprocessing has the lowest fuel price. | 2015 |
| De Jong et al. [192] | A comparison on six conversion pathways was provided for bio-jet fuel production, using techno-economic and pioneer plant analysis. Results show none of the pathways were able to match the petroleum jet fuel price. Their analysis reported that hydrothermal liquefaction and pyrolysis were promising alternatives. | 2015 |
| Patel et al. [55] | A review study reported techno-economic and life cycle assessments for different conversion technologies (gasification, combustion, pyrolysis, liquefaction, carbonization, and co-firing) for bioenergy production. Three major indicators (production costs, functional units, and environmental impacts) were compared. It was concluded that techno-economic assessment on product co-generation and different formation pathways for a product would be useful. | 2016 |

**Table 5**
Portable and fixed bio-refinery characteristics [57,147].

| | Mobile | Transportable | Stationary | Relocatable |
|---|---|---|---|---|
| **Capacity (tons/day)** | 15 | 100 | Variable | 500 |
| **Location** | Logging deck | In-forest | Outside-forest | Outside-forest |
| **Lifetime (years)** | 15 | 15 | Variable | 20 |
| **Salvage Value (%)** | 0 | 0 | 20 | 0 |
| **Mobility Capital ($ thousand)** | 60 | 200 | N/A | – |
| **Capital Cost ($ thousand)** | 1472 | 6031 | 14,300 | – |
| **Operating Cost ($ thousand/year)** | 183 | 3316 | 3052 | – |
| **Setup/Breakdown Time** | 4 h | 4 days | N/A | 2 months |
| **Mileage Charge ($/km)** | 1 | 3 | N/A | 100 |
| **Transport Speed (km/h)** | 40 | 40 | N/A | 80 |
| **Fast Pyrolysis Rate ($/t)** | 162 | 77 | 52 | 61 |
| **Advanced Fast Pyrolysis Rate ($/t)** | 159 | 73 | 48 | 58 |

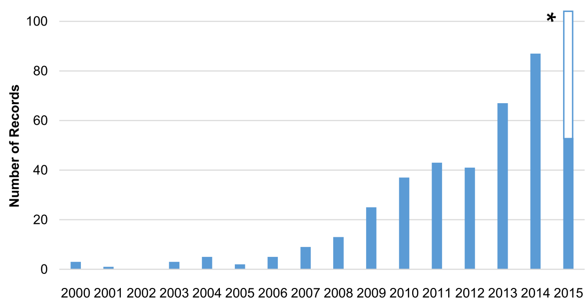


**Fig. 9.** Increase in publications of biomass-to-bio-oil SC research (Jan. 2000 to June 2015,*estimated for July-Dec. 2015).

2) research. The three most productive organizations in each database are the University London Imperial College of Science, Technology and Medicine (sixteen papers), the University of British Columbia (fourteen papers), and the University of Eastern Finland (nine papers); and Iowa State University (seven papers), the University of Alberta (five papers), and the Pacific Northwest National Laboratory (five papers), respectively.

Table 10 presents the top ten research areas in each database, based on number of records. Energy fuels, biotechnology applied microbiology, and engineering are the three most common research areas in biomass-to-bio-oil SC research.

### 4.2. Analysis of citation data

The 394 papers contained in the combined database have been cited by 6957 other publications from January 2000 to June 2015. Fig. 10 indicates the annual increase in the number of citations for the papers contained in the combined databases. Figs. 9 and 10 illustrate that the numbers of publications and citations have been growing exponentially over the past 15 years.

**Table 7**
Top 10 countries based on number of records (between Jan. 2000 and June 2015).

| Keyword Set 1 | | | Keyword Set 2 | | |
|---|---|---|---|---|---|
| Countries/ Territories | Records | % of 277 | Countries/ Territories | Records | % of 126 |
| USA | 80 | 28.9 | USA | 42 | 33.3 |
| Canada | 32 | 11.5 | Canada | 17 | 13.5 |
| Finland | 29 | 10.5 | England | 12 | 9.5 |
| Italy | 26 | 9.4 | Finland | 8 | 6.3 |
| Sweden | 24 | 8.7 | Germany | 7 | 5.5 |
| England | 23 | 8.3 | China | 6 | 4.8 |
| Austria | 19 | 6.9 | Netherlands | 6 | 4.8 |
| Netherlands | 14 | 5.1 | Italy | 6 | 4.8 |
| Norway | 12 | 4.3 | Spain | 5 | 3.9 |
| Germany | 12 | 4.3 | India | 4 | 3.2 |

**Table 8**
Most productive scholars based on number of records (Jan. 2000 to June 2015).

| Keyword Set 1 | | | Keyword Set 2 | | |
|---|---|---|---|---|---|
| Authors | Records | % of 277 | Authors | Records | % of 126 |
| Sowlati, T. | 11 | 3.9 | Kumar, A. | 5 | 3.9 |
| Shah, N. | 9 | 3.2 | Solantausta, Y. | 4 | 3.2 |
| Sikanen, L. | 7 | 2.5 | Czernik, S. | 4 | 3.2 |
| Spinelli, R. | 6 | 2.2 | Brown, R. | 4 | 3.2 |
| Roser, D. | 6 | 2.2 | Wang, Z. | 3 | 2.4 |
| Junginger, M. | 6 | 2.2 | Wang, H. | 3 | 2.4 |
| Gonzalez, R. | 6 | 2.2 | Sadhukhan, J. | 3 | 2.4 |
| Asikainen, A. | 6 | 2.2 | Oasmaa, A. | 3 | 2.4 |
| Saloni, D. | 5 | 1.8 | Ng, K. | 3 | 2.4 |
| Ranta, T. | 5 | 1.8 | Bridgwater, A. | 3 | 2.4 |

The most frequently cited journals in forest biomass-to-bio-oil SC research between January 2000 and June 2015 are reported in

**Table 6**
Top ten journals identified based on number of records (Jan. 2000 to June 2015).

| Keyword Set 1 | | | Keyword Set 2 | | |
|---|---|---|---|---|---|
| Source Titles | Records | % of 277 | Source Titles | Records | % of 126 |
| Biomass & Bioenergy | 38 | 13.7 | Biomass & Bioenergy | 11 | 8.7 |
| Renewable Sustainable Energy Reviews | 17 | 6.1 | Biofuels Bioproducts Biorefining | 11 | 8.7 |
| Applied Energy | 14 | 5.1 | Renewable Sustainable Energy Reviews | 9 | 7.1 |
| Biofuels Bioproducts Biorefining | 13 | 4.7 | Energy Fuels | 9 | 7.1 |
| Journal of Cleaner Production | 12 | 4.3 | Bioresource Technology | 7 | 5.6 |
| Scandinavian Journal of Forest Research | 9 | 3.2 | Green Chemistry | 5 | 3.9 |
| Renewable Energy | 8 | 2.9 | Applied Energy | 5 | 3.9 |
| Bioresource Technology | 8 | 2.9 | Industrial Engineering Chemistry Research | 4 | 3.2 |
| Silva Fennica | 7 | 2.5 | Fuel | 4 | 3.2 |
| Energies | 7 | 2.5 | Journal of Analytical and Applied Pyrolysis | 3 | 2.4 |

**Table 9**
Ten most productive organizations based on number of records (Jan. 2000 to June 2015).

| Keyword Set 1 | | | Keyword Set 2 | | |
|---|---|---|---|---|---|
| Organizations | Records | % of 277 | Organizations | Records | % of 126 |
| Univ London Imperial Coll Sci Technol Med | 16 | 5.8 | Iowa State Univ | 7 | 5.6 |
| Univ British Columbia | 14 | 5.1 | Univ Alberta | 5 | 3.9 |
| Univ Eastern Finland | 9 | 3.2 | Pacific NW Natl Lab | 5 | 3.9 |
| Univ Padua | 8 | 2.9 | Mississippi State Univ | 5 | 3.9 |
| Texas A&M Univ | 8 | 2.9 | Natl Renewable Energy Lab | 4 | 3.2 |
| Finnish Forest Res Inst | 8 | 2.9 | Aston Univ | 4 | 3.2 |
| Univ Utrecht | 7 | 2.5 | Washington State Univ | 3 | 2.4 |
| Swedish Univ Agr Sci | 7 | 2.5 | Univ Manchester | 3 | 2.4 |
| N Carolina State Univ | 6 | 2.2 | Univ British Columbia | 3 | 2.4 |
| Lappeenranta Univ Technol | 6 | 2.2 | VTT, Technical Research Center of Finland | 2 | 1.6 |

**Table 10**
Ten most common research areas based on number of records (Jan. 2000 to June 2015).

| Keyword Set 1 | | | Keyword Set 2 | | |
|---|---|---|---|---|---|
| Research Areas | Records | % of 277 | Research Areas | Records | % of 126 |
| Energy Fuels | 149 | 53.8 | Energy Fuels | 70 | 55.6 |
| Biotechnology Applied Microbiology | 73 | 26.4 | Engineering | 44 | 34.9 |
| Engineering | 68 | 24.5 | Biotechnology Applied Microbiology | 33 | 26.2 |
| Agriculture | 56 | 20.217 | Chemistry | 26 | 20.6 |
| Environmental Sciences Ecology | 50 | 18.1 | Agriculture | 23 | 18.2 |
| Forestry | 45 | 16.2 | Environmental Sciences Ecology | 13 | 10.3 |
| Materials Science | 11 | 3.9 | Materials Science | 6 | 4.8 |
| Chemistry | 9 | 3.2 | Spectroscopy | 3 | 2.4 |
| Thermodynamics | 6 | 2.2 | Polymer Science | 3 | 2.4 |
| Meteorology Atmospheric Sciences | 4 | 1.4 | Thermodynamics | 2 | 1.6 |

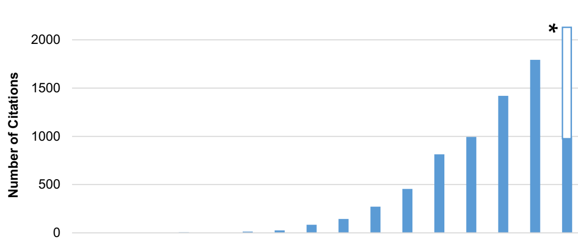


**Fig. 10.** Increase in citations each year (Jan. 2000 to June 2015, *estimated for July-Dec. 2015).

Table 11. Energy and Fuels, the International Journal of Biomass and Bioenergy, and the Journal of Biofuels, Bioproducts & Biorefining are the three most-cited journals in the combined database.

The most frequently cited publications in biomass-to-bio-oil SC research between January 2000 and June 2015 are reported in Table 12. The three most-cited publications are by Czernik and Bridgwater [156], (871 citations); Alonso, Bond, and Dumesic [38], (454 citations); and Lange [171] (189 citations).

**Table 11**
Ten most-cited journals (between Jan. 2000 and June 2015).

| Source Title | Cumulative Citations |
|---|---|
| Energy & Fuels | 1025 |
| Biomass & Bioenergy | 1000 |
| Biofuels, Bioproducts & Biorefining | 692 |
| Green Chemistry | 524 |
| Renewable & Sustainable Energy Reviews | 294 |
| Bioresource Technology | 278 |
| ChemSusChem | 237 |
| Energy & Environmental Science | 183 |
| Energy Conversion & Management | 175 |
| Applied Energy | 158 |

### 4.3. Analysis of keywords

Fig. 11 is a bibliometric map highlighting the frequency of keywords used in the most-cited studies from the combined database (394 papers). The map uses clustering and colors to indicate the frequency of occurrence, with cool colors (blue and green) for less frequent keywords and warm colors (yellow, orange, and red) for more frequently used keywords. Supply chain, emission, environmental impact, ghg, yield, bio-oil, forest biomass, renewable energy, crop, sustainability, transportation, storage, logistics, pretreatment, market, pyrolysis, bio-refinery, and location are highlighted by the obtained visual network as the most-frequently used terms in the identified articles. The less-frequently used terms indicate emerging areas of research that may need further attention from investigators who have the relevant expertise.

### 4.4. Analysis of research methodologies

The qualitative method is used to classify the ten most-cited studies as shown in Table 13 based on the addressed categories and subcategories in Fig. 3. The results indicate conceptual research methods based on literature review are the most prevalent in the context of analytical studies, while, in the context of empirical studies, experimental design was the most applied research method. Since there is a need to improve bio-oil quality and to optimize processes, many studies have focused on empirical exploration to develop commercial processes, e.g., Lin and Huber [83] and Kim et al. [211].

## 5. Discussion

The earliest work summarizing forest biomass SC studies can be traced to Hakkila [93], who argued that the consumption pattern of forest products significantly changed after the first energy crisis. Specially, since 1973, fuelwood has been consumed more than any other biomass product (e.g., paper and wood products). Research has mainly focused on understanding the potential challenges of forest biomass SC, logistics management, and costs related to ground preparation, planting, cultivation, harvesting, collection, processing, in-forest and main-road transportation, pretreatment, and storage. Later studies started focusing on assessing forest-based biomass SCs through quantitative models to calculate the delivered costs of biomass and to identify the relative advantages and challenges of biomass-to-bioenergy supply, such as reduced environmental impacts of bioenergy consumption

**Table 12**
Ten most-cited studies and scholars (between Jan. 2000 and June 2015).

| Authors | Article Title | Source Title | Total Citations | Year |
|---|---|---|---|---|
| Czernik and Bridgwater [156] | Overview of applications of biomass fast pyrolysis oil | Energy & Fuels | 871 | 2004 |
| Alonso et al. [38] | Catalytic conversion of biomass to biofuels | Green Chemistry | 454 | 2010 |
| Lange [171] | Lignocellulose conversion: an introduction to chemistry, process and economics | Biofuels, Bioproducts & Biorefining | 189 | 2007 |
| Demirbas and Balat [149] | Recent advances in the production and utilization trends of bio-fuels: a global perspective | Energy Conversion and Management | 166 | 2006 |
| Luo et al. [146] | Research on biomass fast pyrolysis for liquid fuel | Biomass & Bioenergy | 144 | 2004 |
| Koh and Ghazoul [209] | Biofuels, biodiversity, and people: understanding the conflicts and finding opportunities | Biological Conservation | 134 | 2008 |
| Lin and Huber [83] | The critical role of heterogeneous catalysis in lignocellulosic biomass conversion | Energy & Environmental Science | 133 | 2009 |
| Effendi et al. [210] | Production of renewable phenolic resins by thermochemical conversion of biomass: a review | Renewable & Sustainable Energy Reviews | 126 | 2008 |
| Kim et al. [211] | Biofuels, land use change, and greenhouse gas emissions: some unexplored variables | Environmental Science & Technology | 121 | 2009 |
| Gnansounou and Dauriat [212] | Techno-economic analysis of lignocellulosic ethanol: a review | Bioresource Technology | 116 | 2010 |

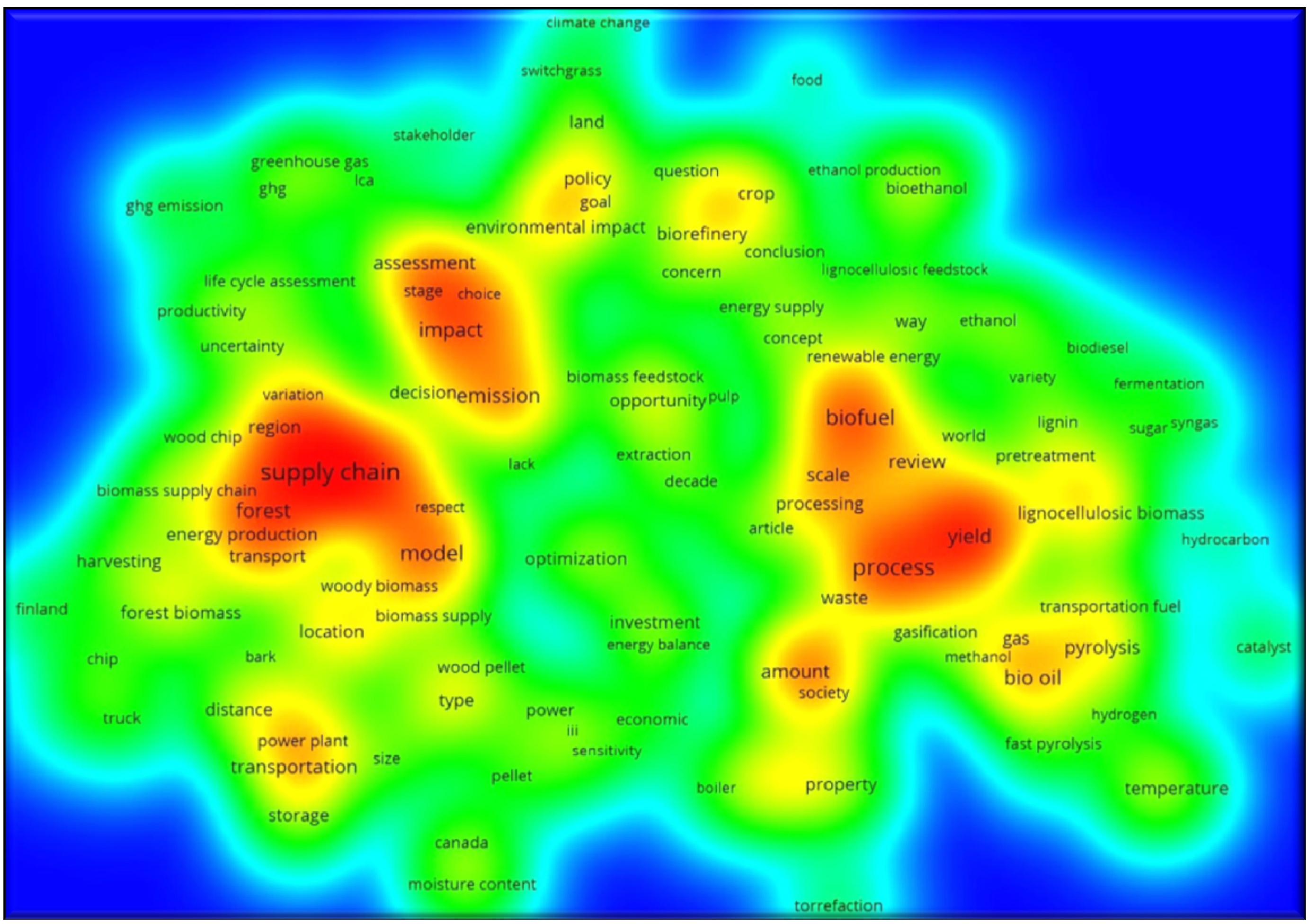


**Fig. 11.** Bibliometric map of keywords (density visualization from VOSviewer software).

[71,213]. Researchers mainly focused on the appropriate planning, management, and operational approaches through network modeling and optimization to recognize the failure or success of a fledgling industry [214]. Mathematical programming and simulation-based modeling are the two main approaches applied to develop SC models [20]. As reviewed above, key contributions have emerged from a range of disciplines, e.g., operations research, SC management, decision making, and sustainability assessment.

Growing use of renewable energy resources is impacting each of the three dimensions of sustainability across the world, which includes access to low-cost, secure energy (economic dimension), reduced net carbon emissions (environmental dimension), and maintaining and developing rural communities (social dimension). It has been reported that logistics is a key activity that can improve the efficiency and profitability of the forest biomass industry [34,116,121]. This review of the state-of-the-art in forest biomass-to-bio-oil SC research found that economic optimization models have been widely applied to assist forest biomass SC logistics

**Table 13**
Classification of the ten most-cited studies.

| Authors | Analytical | Empirical | Classification | Highlight |
|---|---|---|---|---|
| Czernik and Bridgwater[156] | Conceptual | | Lit. Review | Reviewed scientific developments in application of bio-oil and concluded with suggestions for future developments |
| Alonso et al. [38] | Conceptual | | Lit. Review | Reviewed catalytic strategies and addressed the importance of hydrogen in producing biofuels |
| Lange [171] | Conceptual | | Lit. Review | Reviewed the economics of biomass conversion |
| Demirbas and Balat [149] | Conceptual | | Lit. Review | Reviewed recent global advances in production of biofuels |
| Luo et al. [146] | | Experimental | Exp. Design | Developed new pyrolysis system at feed rate up to 20 kg/h |
| Koh and Ghazoul [209] | Conceptual | | Lit. Review | Highlighted positive and negative impacts of biofuel use |
| Lin and Huber [83] | | Experimental | Exp. Design | Developed new catalytic process for production of cost-efficient lignocellulosic biofuels |
| Effendi et al. [210] | Conceptual | | Lit. Review | Reviewed production of renewable phenolic resins by thermochemical conversion of biomass |
| Kim et al. [211] | | Experimental | Exp. Design | Examined several variables (cropping management) that affect GHG emissions of biofuel production |
| Gnansounou and Dauriat [212] | Conceptual | | Lit. Review | Performed techno-economic evaluations of lignocellulosic ethanol production |

decision making. Allen et al. [71] reported that biomass-based renewable energy logistics costs (e.g., processing and transportation) constitute a significant portion of the total costs of biomass-to-bio-oil SC network. Several studies [42,215,216] reported the costs of transporting bio-oil from distributed pyrolysis bio-refineries to a centralized bio-refinery. They used different methods of transportation (i.e., tanker and pipeline), different maximum loads (24–44 t tanker capacity and 560 $m^3$/day pipeline capacity), and also reported on the effects of fixed and variable costs, distance, and approaches on transportation costs of bio-oil.

Over the last 30 years, numerous studies have investigated the economic aspect of biomass-to-bioenergy SCs. In general, bioenergy production costs fall under two major categories: supply costs, which include purchasing and transferring feedstocks, and production costs, which include capital and operational costs of energy conversion. Some past studies have investigated various parameters (e.g., type of feedstock, scale of process, time, and temperature) of conversion technologies to meet economic targets. Past studies have found that some biomass feedstocks, such as lignocellulosic feedstocks, are relatively inexpensive, but are difficult to convert to useful bioenergy. On the other hand, sugars and starches are expensive biomass feedstocks but they are more easily converted to useable energy. There is a tradeoff between feedstock supply cost and production cost. Similar to feedstock delivery, lignocellulosic conversion requires large investments ($50-$100/bbl.), however, collection and delivery of lignocellulosic feedstocks are relatively inexpensive. Therefore, cost reduction in lignocellulosic biomass conversion plays a key role in biomass-to-bioenergy SC implementation [217]. From the review undertaken above, it was found that the key parameters and activities that affect cost modeling and optimization of forest biomass-to-bioenergy SCs include (1) biomass feedstock attributes, e.g., availability, moisture content, bulk density, purchase price, and yield of biomass [37]; (2) harvesting and collection [109]; (3) logistics [178]; (4) pretreatment [56]; and (5) storage [188]. In particular, it was found that the upstream segment of the forest biomass-to-bio-oil SC is influential on the economic viability of the production system [13,30,218].

One of the main roadblocks for bioenergy production is the lack of economical conversion technologies [83]. In addition to logistics, conversion and post-conversion technologies can affect the economic feasibility of using forest biomass. While capital costs of refinery facilities do not typically scale linearly with capacity [148], the operational cost is more directly impacted by the scale of the system. Thus, there is a significant need for studies focusing on upscaling biomass conversion and post-conversion processes to accelerate the commercialization of biomass-to-bioenergy production technologies. This study gives decision-makers a base for substantiating further development of logistics systems and pretreatment technologies.

Biomass quality attributes (e.g., energy content, moisture content, particle size, ash, and contaminant content) affect the processing operations (e.g., chipping, grinding, and sorting), transportation attributes (e.g., type, capacity, and distance), and conversion and post-conversion technologies properties (e.g., resource type, product type, and capacity). Biomass yield and bulk density are two key factors impacting transportation cost – higher yields lead to reduced truck travel distance and higher bulk density reduces the number of truck trips [13]. A standard tanker truck can carry bio-oil with an energy content of 558 GJ (13–18 MJ/kg), which is twice the energy content of wood chips carried by a chip van [120].

Several studies investigated the upstream segment of biomass to bio-oil SC networks. This study extends prior work by incorporating recent research into mixed-mode networks of mobile and fixed refineries to trade off between processing and transportation costs [29,219]. Consequently, successful mobile refinery development will enable locating facilities in the field near biomass sources, thus enabling transport of higher energy density product to a central facility. It was also found that biomass-to-bioenergy SC literature has not paid close attention to biomass and bioenergy storage strategies. The lowest cost solution is adopted in most cases, without considering the effects of other biomass storage solutions that can reduce overall cost [178]. Simultaneous consideration of all entities in the upstream segment could lead to strategies for the economic success of a forest fuel development project. Future studies, for instance, should evaluate the biomass storage methods addressed above, as well as novel storage strategies to minimize system costs.

## 6. Conclusions and future direction

The presented study used both a narrative review and a systematic review of the literature to assess the linkages among current studies and to identify the potential technologies and practices that would address existing gaps and future perspectives within the upstream segment of biomass-to-bioenergy SC. From the narrative review, it is clear that most studies that examine the upstream segment of biomass-to-bio-oil SCs focus on isolated problems within three main activities: harvesting, logistics, and storage. From the systematic review, it is apparent that forest biomass-to-bio-oil SC research has been a rapidly growing area of interest over the last 15 years. From both reviews, it is evident that there is a need for more focused research on forest biomass-to-bio-oil SC issues, specifically on pretreatment process development (e.g., pyrolysis) and implementation at the industry level. Also, there is a need for more investigation into modeling and optimization of pretreatment as a part of the upstream segment of biomass-to-bioenergy SCs. The review highlights the gap between work in literature and industry practice.

While many studies predominantly explored the complete SC (i.e., upstream, midstream, and downstream) to tackle sustainability issues (i.e., economic, environmental, and social), there is a dearth of literature for detailed analysis of each individual segment of the SC. Exploring and addressing the gaps in each segment can raise the awareness of decision makers and, subsequently, aid in identifying alternative ways of making business more robust and sustainable. In summary, this study reveals some of the gaps in research related to the upstream segment of forest biomass-to-bioenergy SCs. Specifically, the following potential paths for a future research are defined:

- Development of biomass SC optimization models for integrating pretreatment processes into the upstream segment of forest biomass-to-bioenergy SCs.
- Exploration of pretreatment processes to identify economic, environmental, technological, and political challenges and barriers to implementation.
- Development of an integrated techno-economic assessment method to evaluate the investment factors by comparing different system designs and assumptions.
- Development and implementation of novel pretreatment processes that could be adopted by industry into practice (e.g., transportable bio-refinery facilities).
- Exploration of the state-of-the-art within other disciplines to integrate adopted methods and approaches (e.g., mathematical analysis and experimental design).
- Exploration of issues related to the existing metrics and measures for optimization based on triple bottom line sustainability.

Further, there is a need to develop a detailed research plan for each of the paths proposed. Investigations into biomass-to-bioenergy SCs are increasing due to internal and external stakeholders' needs, which include growing demand for bioenergy and for reduction of economic and environmental impacts. This study analyzed the nature of existing publications, citations, keywords, and research methodologies. Limitations of this study include the use of specific combinations of keywords for generating a database (394 papers) of prior research from the Web of Science™. Thus, this approach may have omitted some related papers from consideration. It is hoped this study will lead to production of more sustainable bioenergy and chemical products from forest biomass.

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