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Review

Transportation planning in multiple bioenergy value chains: A literature review

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A B S T R A C T

Transportation of biomass has long been a significant obstacle to the efficient and large production of bioenergy, as it accounts for a considerable portion of the value chain costs. Over the past two decades, researchers have developed and analyzed suitable supply chains, equipment, and technology for biomass utilization. With state-of-the-art systems now in place, it is possible to optimize the transportation planning efficiency at the operational level to achieve both economic and social objectives. This optimization ensures that the right resource is selected from the right supplier to produce a more sustainable energy source. This article proposes a literature review assessing the current status on biomass transportation and identifying the trends and ideas for improvement of biomass transportation planning, specifically at the operational level. A total of 146 publications from 2009 to 2023 were selected using keywords related to transportation, biomass, and improvement. The papers were reviewed to investigate the methodologies, mechanisms, and key metrics used by the authors to efficiently implement and support transportation planning within the biomass value chain. Our review identified seven transportation efficiency mechanisms (EMs): resource sharing, joint decision making, multimodal integration, transit preparation, financial agreement, information sharing, and local feedstock integration. We also evaluated the consideration of the economic, environmental, and social factors in assessing the performance of these EMs. Our findings revealed a scarcity of research in operational-level transportation planning for biomass that incorporates EMs, particularly the transportation resource sharing EM, even though it has proven to be profitable at the tactical level. There is also a lack of assessment of these EMs considering the three dimensions of sustainability: economic, environmental, and social.

1. Introduction

As a solution to the heavy dependence on fossil fuels, biomass is a renewable resource that captures carbon dioxide during its growth. It can be grown, collected, utilized, and replaced rapidly, without diminishing natural resources, in contrast to fossil fuels that take millions of years to form (Yue et al., 2014). To efficiently exploit such a resource, the value chain needs to encompass four main stakeholders, namely biomass suppliers, intermediate storage/satellite yards (i.e., terminals), biorefinery plants (i.e., bioenergy producers), and end-customers for bioenergy. Transportation, which involves the movement of materials/products between these sites, accounts for about one-third of the total logistics cost of the value chain (Malladi and Sowlati, 2017). In the upstream part, biomass is transported from suppliers either directly to bioenergy producers or indirectly through intermediate terminals. In the downstream segment, final products, such as transportation fuel, heat, electricity, and/or other biomaterial, are transported from bioenergy producers to the end users. Bioenergy producers serve as the connection between upstream and downstream transportation (Ebadian et al., 2021; Malladi and Sowlati, 2018).

Fig. 1 illustrates the key decisions relevant to each stage of the biomass value chain, including vehicle scheduling/routing and material flow, which are often studied alongside the other decisions in the Figure. At supplier sites, decisions involve biomass production, storage, inventory, and preprocessing. Intermediate terminals are properly located sites, to handle feedstock preprocessing, to manage storage and inventory, and to define and conduct pre-treatment. Bioenergy producers, the main stakeholders, focus on conversion planning, conversion technology selection, supplier selection, plant location-allocation, sales planning, and biomass pre-treatment, preprocessing, storage, and

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inventory. Bioenergy products storage and inventory decisions can occur at both plant and customer sites.

Among all challenges faced by the biomass value chain, transportation appears as a key activity to optimize for achieving efficient and large-scale production of bioenergy. Despite its global abundance, biomass is not always available in the right place, form, or at a reasonable cost (Veringa Niemela et al., 2010). Large volumes and relatively long transportation distances, coupled with rising fuel prices and environmental concerns make the improvement of transportation planning necessary (Frisk et al., 2010). Transportation is particularly complicated and expensive in the biomass sector due to the material's unfavourable handling and transportation characteristics, including bulkiness, relatively low energy densities, high moisture content, and poor flowability (Mobini et al., 2014). These challenges limit biomass's potential contribution to energy. For example, forest biomass contributes only 5–6 % to Canada's energy supply, despite its potential to contribute 18 % (Mobini et al., 2014). As a result, even a minor decrease in transportation costs could result in significant savings (Malladi and Sowlati, 2017).

In the literature, in spite of its importance, transportation has received fewer attention compared to other stages of the biomass supply chain, including harvesting, collection, preprocessing, and conversion processing (Ko et al., 2018). Malladi and Sowlati (2017) reviewed forest transportation optimization at the operational level considering forest products, i.e., logs, biomass, pulp, and furniture. They concluded that the authors usually focus on logs transportation, while forest-based biomass, pulp, and furniture transportation received less attention. Ko et al. (2018) reviewed transportation and logistics of biomass from forest, agriculture, and municipal waste for the period 1990–2016, discussing four critical issues that significantly impact the viability of the supply chain: transportation/logistics cost, shipping distance, plant capacity, and system efficiency. Their review identified four options to increase the efficiency of biomass transportation and logistics: fleet operations, mode selection, utilizing storage facilities, and management of uncertainty. They assessed the selected papers based on six parameters: feedstock, location, in/outbound transportation, mode, products, and analysis tools. Malladi and Sowlati (2018) reviewed forest and agriculture biomass logistics operations -harvest and collection, storage, transportation, and pre-processing- focusing on important features and their use into mathematical optimization models. They suggested that future research should consider social and environmental objectives, develop solution techniques, and create user-friendly decision support tools. Considering forestry biomass, Kühmaier and Erber (2018) reviewed the publication in European forest fuel supply chain from 2007 to 2016 in terms of Comminution, Transport & Logistics. Their reviewed papers suggested that transportation of biomass can be more efficient by improving the efficiency of fuel wood transportation, conducting economic and environment assessments of supply chains, selecting suitable transportation modes based on distances (road, rail, and/or water transport), coordinating supply processes like chipping and transportation operations, and employing multi tree handling in fuel wood harvesting. Acuna (2017) provided an overview of timber and biomass optimization models in the forest industry, focusing on transportation operations in strategic, tactical, and operational levels. The review paper revealed that timber and biomass transportation problem are commonly formulated as linear programming models, with extensions to include backhauling to improve transportation planning efficiency. Two decision support tools, MCPLAN and FastTRUCK, were also described for optimal transportation planning of timber and biomass from the forest to mills and energy plants and for efficient trucks scheduling and routing between these supply and demand points, respectively. Audy et al. (2023) reviewed planning models and decision support systems for routing and transportation in general forestry. They classified different types of routing problems and discussed which models are common to use. They also described systems developed for planning.

Most of the existing review papers concerned problems in timber and/or forestry biomass transportation, such as (Acuna, 2017; Audy et al., 2023; Kühmaier and Erber, 2018; Malladi and Sowlati, 2017). Only Ko et al. (2018) and Malladi and Sowlati (2018) considered other sectors of biomass like agriculture and municipal waste as well. However, all these papers focused on reviewing the development of transportation models rather than the transportation efficiency mechanisms

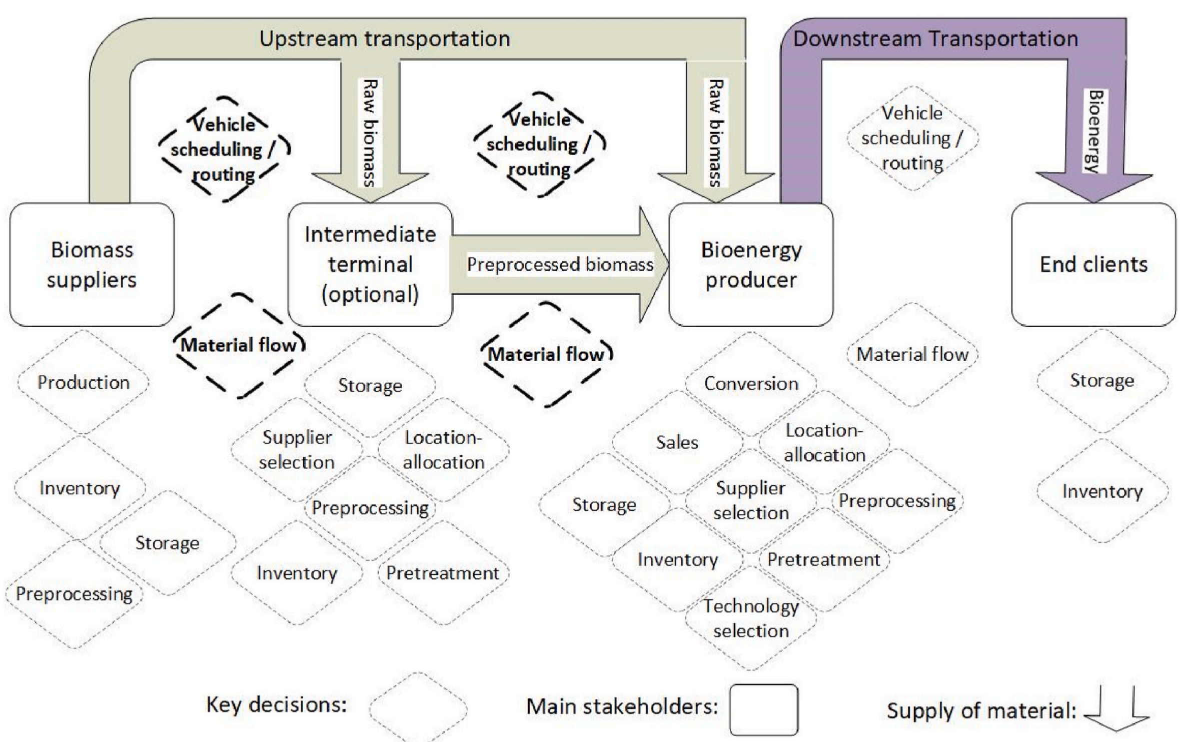

Fig. 1. Main stakeholders of biomass value chain and its key decisions. The decisions in bold are what we aim to look at in this review paper.

(EMs) to implement so as to improve it. Efficiency of biomass transportation is quite a new subject and has gained more interests recently, but to the best of our knowledge, no paper reviewed the recent publications regarding such a subject. Ko et al. (2018) gave a few suggestions for increasing transportation efficiency while reviewing studies published before 2016. Therefore, it appears that a research gap in the literature remains concerning the need for a comprehensive exploration of the EMs to use in order to enhance biomass transportation planning across the three biomass sectors: forestry, agriculture, and municipal waste. We also noted that while numerous studies reviewed the entire biomass supply chain, such as (Acuna et al., 2019; Ba et al., 2016; Cambero and Sowlati, 2014; Zandi Atashbar et al., 2018), only three studies specifically focused on exploring the current status of biomass transportation in terms of its main characteristics: (Ko et al., 2018; Malladi and Sowlati, 2017, 2018).

This paper therefore offers a distinct perspective compared to the previous review papers by highlighting the EMs and methodologies used to improve biomass transportation planning in the three sectors, while providing mechanisms and methodologies that could potentially be exploited in biomass transportation planning in future research. The three cost factors, including economic, environmental, and social, that can be calculated for evaluating the performance of the methodologies and mechanisms are also presented. In particular, the paper proposes a systematic literature review on biomass transportation planning, focusing on upstream transportation, including vehicle scheduling/routing and biomass flow among suppliers, terminals, and bioenergy producers. It aims at identifying potential efficiency mechanisms (EMs) for improving the process while better understanding the current state of research in this field.

To achieve this goal, three research questions were defined, concerning the methodologies to use (question 1), the mechanisms to exploit (question 2), and the metrics to establish (question 3) so as to implement and improve the transportation planning. To answer the research questions, a total of 146 papers published from 2009 to 2023 were reviewed. These papers were found using three sets of English keywords related to transportation, biomass, and improvement, encompassing 28 specific keywords. The selection process began with over 6000 initial papers, from which the final 146 were chosen by following the systematic literature review (SLR) methodology and conducting citation tracing on the most relevant papers identified through the SLR.

Based on the analysis of the selected articles, it was found that optimization models seem particularly useful for the implementation of biomass transportation planning, while simulation models were conducted to evaluate the performance of the methodologies. GISs (Geographic Information Systems) were also frequently used beside these models for real-world data calculations. The analysis also led to the identification of seven EM categories: resource sharing, joint decision making, multimodal integration, transit preparation, financial agreement, information sharing, and local feedstock integration. Incorporating these EMs into the optimization models appear to reduce transportation cost and time more than the reductions achieved by standard optimization models. These EMs seem to have impacts on all the three dimensions of sustainability, economic, environmental, and social, but environmental and social metrics appeared less frequently to assess the performances.

The reminder of the paper is as follows: Section 2 describes the methodology used to conduct the review. Section 3 answers the three research questions, each followed by a critical discussion. Section 4 and 5 discuss the findings and conclude with future research directions.

2. Systematic literature review (SLR) methodology and scope

In order to identify methodologies, mechanisms, and metrics used to enhance biomass transportation planning, a systematic literature review (SLR) was conducted. The review followed the six-step methodology outlined by Durach et al. (2017). The first step involved defining the research questions. The second step included determining the required characteristics of primary studies. According to this step, we identified the relevant keywords. The third step referred to finding a sample of potentially relevant papers. The fourth step involved narrowing down the number of studies to the most relevant sources, as shown in Fig. 3. The fifth and sixth steps included synthesizing the literature and reporting the results, respectively. The research questions considered were as follows:

RQ1: Which methodologies are used to implement transportation planning in the biomass value chain?
RQ2: What are the mechanisms used to improve transportation planning?
RQ3: What are the key metrics used to measure the performance of the proposed planning, especially from a sustainability point of view?

The three sets of keywords, introduced in Fig. 2, were used to identify the potentially relevant papers. After testing different databases and different sets of keywords, we selected the Web of Science (WoS) database and three keyword sets, as shown in Fig. 2 (Set 1, Set 2, and Set 3). The process for selecting the database and keywords involved identifying a small number of highly relevant papers and checking if the search results for specific keyword sets in a database covered a larger number of these papers. WoS and the keyword sets in Fig. 2 achieved this goal. To ensure no relevant papers were missed, we traced the citations of the final set of selected papers by the keyword search process. These sets were searched within “Keyword plus”, “Keyword”, “Title”, and “Abstract (Topic)” on WoS. “Keyword plus” contained a set of keywords chosen by WoS for each article. The keywords within each set were combined using “OR”, and all three sets were combined using “AND”. Sets 1 and 2 helped us find an extensive body of research on planning biomass transportation. Adding Set 3 allowed us to focus on studies involving structures and mechanisms to improve transportation planning. Our keyword search initially yielded 6373 papers.

Fig. 3 outlines the process for selecting the most relevant publications in three phases. The ***Limitation phase*** involves narrowing down the sources based on specific characteristics. We restricted the sources to those published within the last 15 years, from 2009 to 2023, resulting in a total of 5468 publications. This includes papers published online in 2023. We noted a scarcity of publications before 2009 focusing on improving biomass transportation, indicating that this topic is novel in the literature. A possible reason for this could be the introduction of Renewable Energy Directive (RED) by European Union (EU) Commission in 2009, promoting the use of energy from renewable sources (“Renewable energy directive,” 2009). We further refined the sources to include only articles, proceeding papers, and book chapters published in English, thereby slightly narrowing them down to 5379 sources. Among these, 18 duplicates were identified and removed.

The ***Screening phase*** shows how the irrelevant publications are excluded through a three-step screening process. A vast majority (over three-quarters) were identified as irrelevant and subsequently removed after screening their titles and a quick glance at the abstracts. This large number of irrelevant papers was partly due to the generality of some of the keywords considered. For instance, the keyword “chips” frequently appears in papers within the field of chemistry and physics, often referring to a tool named “chip”. Additionally, numerous papers related to topics such as Covid 19, healthcare, food, cold chain, etc. were removed. After this initial screening, 1261 relevant publications were identified. Then, abstracts, introduction, and conclusion were screened in two stages, which resulted in a final selection of 132 publications. In this procedure, we observed that the keyword “transportation” yielded many papers studying transportation biofuel production, rather than transportation of biomass, which is our primary focus. These papers were identified and removed. Moreover, we noted that the keywords

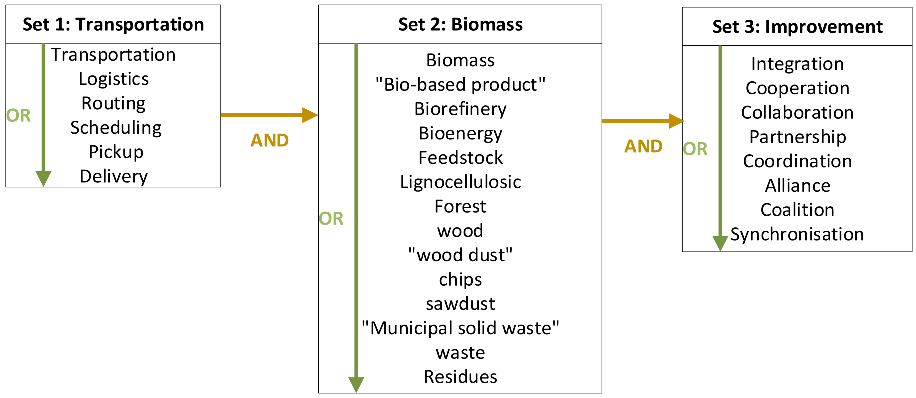

Fig. 2. Sets of keywords used for the Systematic Literature Review (SLR).

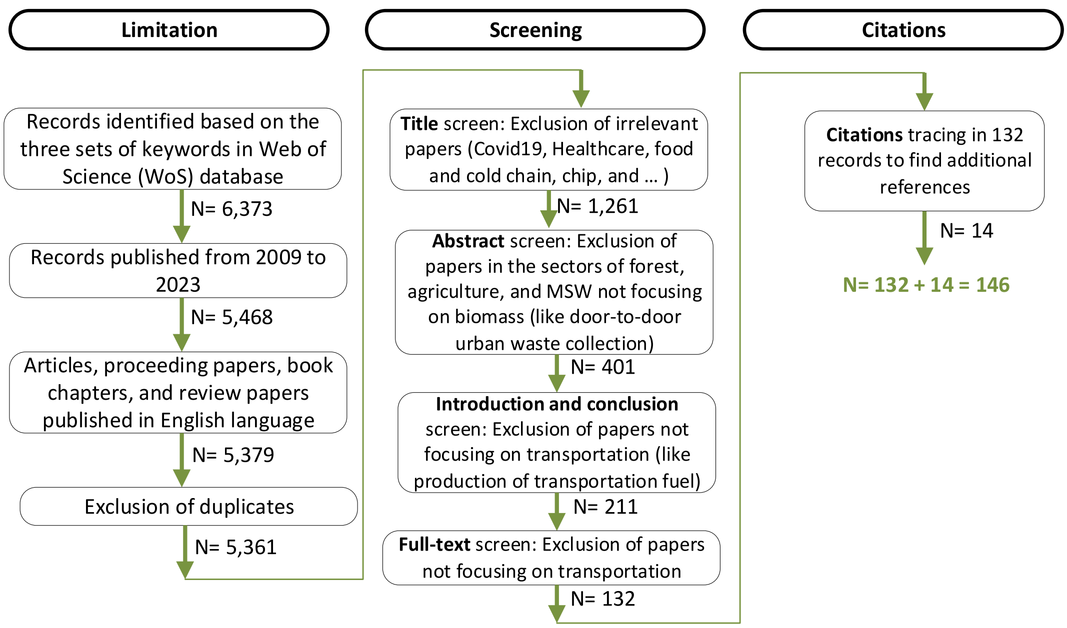

Fig. 3. Characterization and selection of the most relevant articles for the research.

"waste" and "forest" were excessively broad, covering studies on urban waste transportation and transportation of other forest products (e.g., for pulp and paper industries) without the purpose of producing bioenergy from biomass.

The SLR methodology was enhanced by adding a ***Citations tracing*** phase. In this phase, we tracked the citations in the 132 papers to identify additional references that we might have missed during the keyword search process, especially those relevant to operational-level transportation. This process added 14 more studies. Ultimately, we fully screened a total number of 146 papers. The next section will highlight what have been found after analyzing the scientific content of each paper.

3. Result of the SLR

Section 3 presents the results of this paper and is divided into four subsections. Subsection 3.1 outlines the general characteristics of the selected papers based on their biomass sectors and publication features. Subsections 3.2, 3.3, and 3.4 answer the three research questions, each concluding with a critical discussion of the main findings, trends, and future directions.

3.1. Descriptive results

Common feedstocks for bioenergy production come from three sectors: forest, agriculture, and municipal waste (Ko et al., 2018). Fig. 4 illustrates various value chains in the three sectors and the number of papers that covered each of them. It should be noted that the papers mentioned in Fig. 4 exceed 146, which is the total number of reviewed papers. This is because some papers studied multiple value chains so they were counted multiple times.

Forest sector consists of two main materials, i.e., roundwood and forest fuel. Roundwood is the common name for saw logs and pulp logs (Flisberg et al., 2015), which are input materials to sawmills and pulp and paper mills (Frisk et al., 2010). 36 of the reviewed papers studied this value chain. Forest fuel consists of primary and secondary forest fuel (Flisberg et al., 2015). Primary forest fuel includes tree tops and branches, stumps and damaged logs, like wind felled and decayed, and small trees from thinning operations, which have not undergone any chemical processing and are used only for energy purposes (Flisberg et al., 2015; Guajardo et al., 2018b). Secondary forest fuels refer to other by-products generated by the industry, including bark, sawdust, and shavings, mainly utilized for energy within mills. Any excess is either sold to biofuel manufacturers, heating plants, or the chipboard industry (Flisberg et al., 2015). 45 and 16 of the reviewed papers studied primary

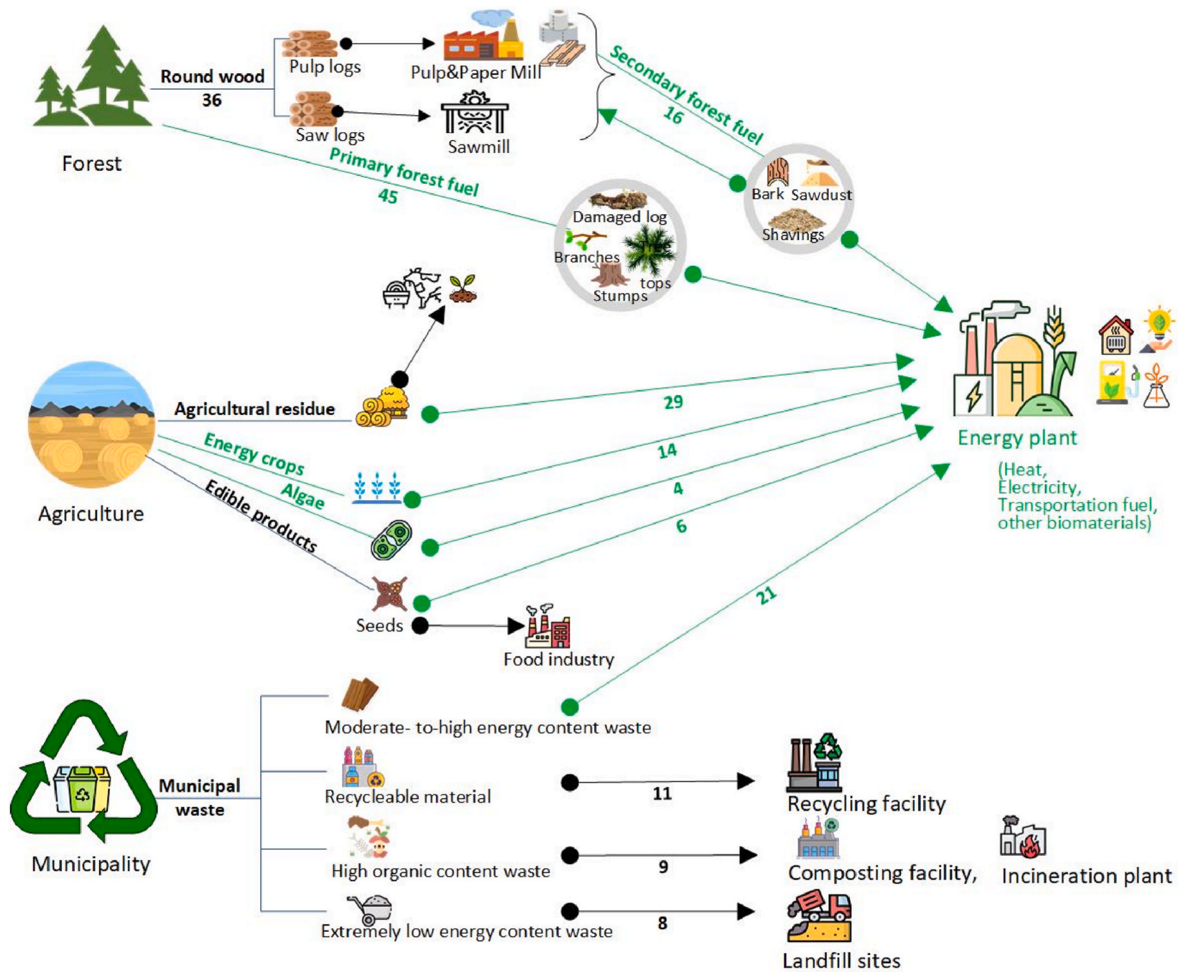

Fig. 4. Number of reviewed papers in each supply chain streams. The color green is used to show the number of papers that consider supply of materials to energy plants, and the color black is used for those considering supply of any other product to other plants. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

and secondary forest fuel value chain, respectively.

Agriculture sector consists of four main streams of value chain: agricultural residue, energy crop, algae, and edible products. 29, 14, 4, and 6 of the reviewed papers studied these, respectively. Agricultural residue refers to the leftover materials such as straw, stover, and husk that remain after harvesting food crops. According to Ebadian et al. (2014), a portion of available agricultural residue is deducted from its total volume for livestock requirement and the soil conservation, at rates of 5 % and 30–50 %, respectively. Energy crop consists of any crop cultivated mainly for the purpose of energy, including switchgrass, triticale, sorghum, rapeseed, miscanthus, cardoon, etc. Microalgae can be cultivated in open ponds, such as extensive and artificial raceway ponds, or in closed systems like photo-bioreactors (Čuček et al., 2014). The fourth value chain is food-based products, which are mainly sent to food industry, but can also be used as input material for biorefineries (e.g., corn).

Municipal Waste (MW) is divided into four categories: waste with moderate-to-high energy content, recyclable materials, waste with high organic content, and waste with extremely low energy content. These are sent to waste-to-energy facilities (21 papers), recycling facilities (11 papers), composting facilities (9 papers), and landfills (8 papers), respectively (Islam et al., 2023). Only 12 of the total papers do not aim at transporting MW to energy production sites. Some examples of waste with moderate-to-high energy content are organic waste, manure, waste fats, and oils and greases. Recyclable materials include glass, metal, paper, etc.

Fig. 5 (left) presents a breakdown of the reviewed papers across forest, agriculture, and MW sectors. The forest sector stands out as the primary focus of more than half of all papers found (75 papers). Studies on agriculture and MW sectors are notably fewer, with 30 and 28 papers respectively. We hypothesize that the reason for most of the publications focusing on forest sector is due to our study's emphasis on transportation efficiency, which is more extensively studied in forest sector -both biomass and roundwood transportation. A limited number of papers studied multiple sectors, i.e., while combined forest and agriculture received the attention of 9 papers, only 4 papers considered the three sectors all together.

Fig. 5 (right) illustrates the breakdown of the selected papers based on the type of final products, including bioenergy, heat, other energy types, transportation biofuel, electricity, and other mills' products. Once again, the total number of papers exceeds the actual number of papers reviewed (146) because one publication with multiple final products is counted separately. Table 1 shows the final products included in each category. Under the category of bioenergy, we included papers wherein the destinations of biomass transportation are either biorefineries, terminals, waste-to-energy plants, or incineration plants for energy recovery, although the types of recovered energy are not specifically determined. As expected, energy production, which is the main focus of this paper, is the purpose of more than 71 % of the studies (104 papers). The number of papers under the other mill's products category are equivalent to the black arrows shown in Fig. 4, in the forest and MW sectors. The green arrows represent those aiming at energy production.

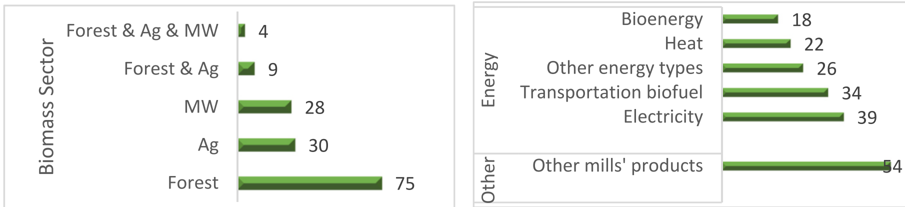

Fig. 5. Number of reviewed papers based on biomass sectors (left) and final products (right). (Ag: Agriculture).

Table 1
Category of final products.

Category	Final products
Bioenergy	The destinations of biomass transportation are either biorefineries, terminals, waste-to-energy plants, or incineration plants for energy recovery, although the types of recovered energy are not specifically determined
Heat	District Heating (DH), combined heat and power (CHP), heating energy, residential heating, steam, renewable heat
Electricity	Combined heat and power (CHP), power, grid electricity, off-grid electricity, bioelectricity, thermal power
Other energy types	Pellet: Wood-pellets, switchgrass-pellets, and agriculture-pellets Fertilizers: Agricultural fertilizers, digestate (byproduct as fertilizer), bioslurry from biogas system, compost Biochemical: Levulinic acid and formic acid, furfural and methanol, and lignin Biogas: Biogas, LBG (liquefied biogas)
Transportation biofuel	Bioethanol, biodiesel, FT-diesel, hydrogen, green gasoline, alternative jet fuels, sustainable aviation fuel (SAF), liquid biofuel, maritime biofuels (biobunkers), biofuel, bio–synthetic natural gas (SNG), bio-oil
Other mills' products	Lumber, recycled products, different forest products (e.g., sawn wood, pulp and paper, cabinet, wood floor, furniture, engineered wood product), hardboard, wood boards, lateral board, square board, pruned board, long board, pruned log, disposal of waste in landfills

Fig. 6 represents the number of reviewed papers per year of publication. It is evident that interest in this field has grown annually, particularly since 2014. In Fig. 7, the number of papers is depicted based on the journals of publication, with a focus on those that appeared at least twice. 'APPLIED ENERGY' and the 'JOURNAL OF CLEANER PRODUCTION' emerge as the most frequent, with 11 papers each.

3.2. Methodologies used in the articles (RQ1)

The first research question explored what methodologies were used to address transportation planning of biomass, the focus of this study. Transportation operations might be studied as a standalone issue or alongside other aspects. Fig. 8 illustrates the focus of the reviewed papers, which includes transportation planning, network design, vehicle routing/scheduling, conversion planning, production planning, life cycle assessment (LCA), and techno-economic assessment (TEA). Three of the references -(Ahl et al., 2020; Flodén and Williamsson, 2016; Palander, 2022)- did not directly address the aforementioned problems but employed surveys to assess the feasibility of certain transportation structures and strategies through real-case interviews.

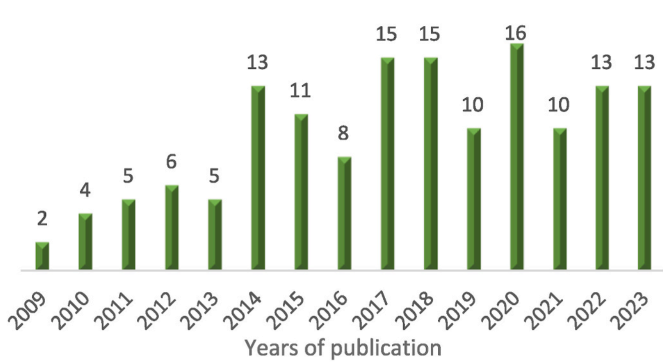

Fig. 6. Number of reviewed papers per year of publication.

As the main focus of this review paper is on transportation decisions, 72 % of the papers explored transportation planning (e.g. Zhang et al. (2017)) and various vehicle routing/scheduling problems (VRPs) such as pure VRP (e.g. Guajardo (2018)), vehicle scheduling (e.g. Wan et al. (2022)), inventory routing (e.g. Vidovic et al. (2014)), location routing (e.g. Shi et al. (2023)), and production routing (Alarcon-Gerbier et al., 2023). Transportation planning involves considering transports as flows between supply and demand points (Rönnqvist et al., 2023). Inventory planning is often studied alongside the main problems when multiple planning periods are involved, as observed in 16 % of the papers.

The other five categories were either studied alongside transportation planning and vehicle routing/scheduling or addressed as standalone issues considering transportation parameters such as distances and modes. Network design, the second most frequent category studied by 30 % of the papers, includes facility location problems (e.g. Burnard et al. (2015)), facility location-allocation problems (e.g. Mullins et al. (2014)), production capacity planning (e.g. Tucho et al. (2016)), storage capacity planning (e.g. Santibañez-Aguilar et al. (2017)), biomass availability assessment (e.g. Richardson et al. (2011)), supply selection (e.g. Golberg et al. (2012)), road construction (e.g. Naderializadeh et al. (2022)), road selection (Rönnqvist et al., 2017), and road expansion (Hajibabai and Ouyang, 2013). Over half of these problems were examined along with transportation planning and vehicle routing/scheduling.

Production planning and harvesting planning were studied alongside transportation planning and vehicle routing/scheduling by 14 % and 8 % of studies, respectively. Only Khaloie et al. (2021) focused solely on production planning without considering transportation, but it was included in our review because of the mechanism they used. Harvesting planning refers to how, when, where, and in what quantity raw feedstock will be harvested (Naderializadeh et al., 2022), while production planning refers to deciding how, when, and in what quantity final bioenergy products will be produced (e.g. Gao et al. (2019)). LCA and TEA are two tools used to evaluate the economic and environmental performances and feasibility of bioenergy production (Guimarães et al., 2023). 6 % and 5 % of the reviewed papers studied LCA and TEA problems, respectively. Guimarães et al. (2023) studied both LCA and TEA.

Figs. 9 and 10 provide a breakdown of papers based on decision levels, analytical methodologies, solution approaches, modeling tools, and the countries of the case studies considered. The Figures reveal that studies mainly focused on providing optimization models (128) for strategic (65) and tactical (65) levels of decision-making. These studies predominantly utilized exact solution approaches (130), typically mixed-integer linear programming (MILP) models (63), to address the problems at these levels, with a significant number of case studies conducted in either Sweden, Canada, the United States, or China (combined 72).

Regarding the definitions of decision levels provided by Frisk et al.

Fig. 7. Number of reviewed papers per scientific journal.

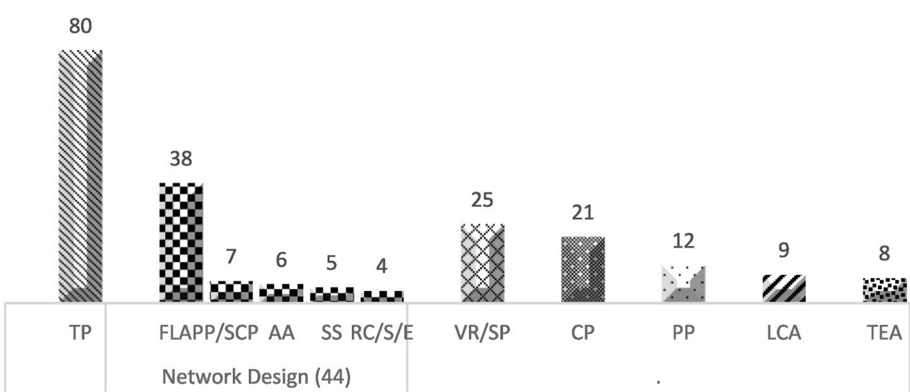

Fig. 8. Number of papers per problem category (TP: Transportation (and/or Inventory) Planning; FLAP: Facility Location-Allocation Problem; P/SCP: Production/ Storage Capacity Planning; AA: Availability Assessments; SS: Supply Selection; RC/S/E: Road Construction/Selection/Expansion; VR/SP: Vehicle (and/or Inventory) Routing/Scheduling Problem; CP: Conversion Planning; PP: Production Planning; LCA: Life Cycle Assessment; TEA: Techno-Economic Assessment).

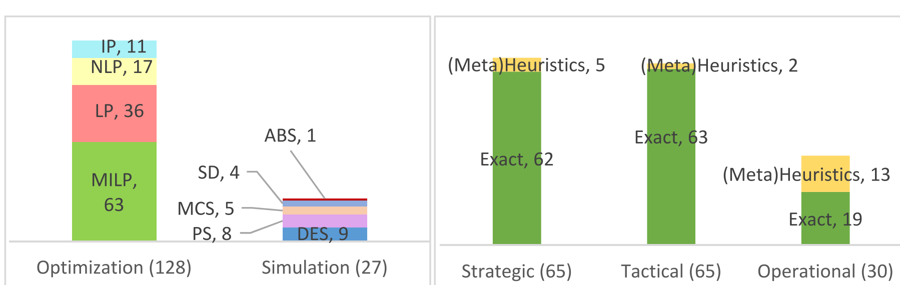

Fig. 9. Number of papers with respect to their (left) methodologies and modeling tools (right) decision levels and solution approaches. (LP: Linear Programming; IP: Integer Programming; MILP: Mixed Integer Linear Programming; NLP: Non-Linear Programming; DES: Discrete Event Simulation; SD: System Dynamic; PS: Process Simulation; MCS: Monte Carlo Simulation; ABS: Agent-Based Simulation.)

(2010) and Rönnqvist et al. (2023), strategic decisions are made for long-term, over a horizon of more than one-year, and include decisions related to LCA, TEA, and network design such as facility location, production capacity planning, road construction, biomass availability assessment, and supply selection. Tactical decisions occur in medium-term, ranging from one month to a year, and primarily involve transportation planning. Operational decisions cover a horizon of less than a month and involve detailed decisions like determining individual truck routes and schedules. Harvesting and production planning can occur at all three levels, depending on how detailed are the decisions. Transportation decisions can also occur at all three levels (Rönnqvist et al., 2023) such as road construction at the strategic level, forward/backward transportation flow at the tactical level, and trucks routing at the operational level.

The researchers employed both optimization and simulation models as analytical methodologies. Optimization models typically involve data

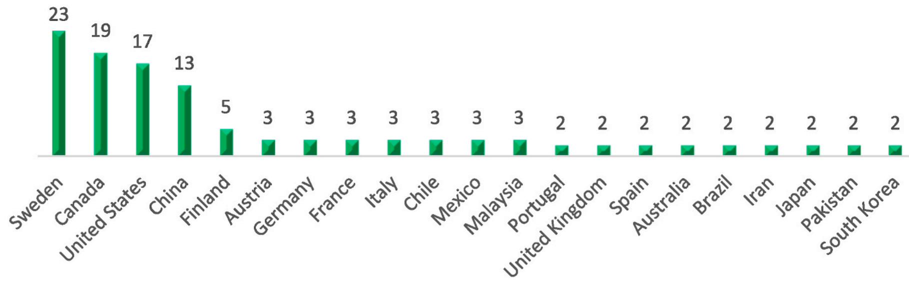

Fig. 10. Number of papers per country of case studies.

processing using mathematical equations or algebraic expressions, while simulation models consist of a repetitive series of system operations to mimic real-world conditions (Ko et al., 2018). Optimization models utilize tools such as MILP, Linear Programming (LP), Nonlinear programing (NLP), and Integer Programming (IP). Simulation models use tools like Discrete Event Simulation (DES), Process Simulation (PS), Monte Carlo Simulation (MCS), System Dynamic (SD), and Agent Based Simulation (ABS). GIS is frequently integrated with these models for data calculation. For example, Richardson et al. (2011) imported road data into ArcGIS 9.3 to estimate both time-based and distance-based transportation costs, using the physical features of roads within the study area surrounding a proposed cogeneration heat and power plant in White Swan, Washington. They analyzed the effects of land ownership, and assessed the impact of uncertainty in cost and supply on the final supply curves.

Both exact and (meta)heuristics solution approaches were used to solve the models. Nearly 90 % (130) of the papers applied exact methods; 35 of these used CPLEX or GUROBI solvers directly on optimization Software like GAMS and AMPL or used Decision Support Systems (DSSs). FlowOpt is a DSS used for roundwood transportation planning by Guajardo et al. (2016), Rönnqvist et al. (2018), Audy et al. (2012a), Guajardo and Rönnqvist (2015), D'Amours and Rönnqvist (2013), Frisk et al. (2010), and Flisberg et al. (2018). FuelOpt is the modified version of FlowOpt used for forest biomass transportation planning by Flisberg et al. (2015, 2012), and Guajardo et al. (2018a). All these studies were conducted at the tactical level. Iqbal et al. (2022), Gebresenbet et al. (2018), and Hu et al. (2017) also provided Excel-based DSS, EuroPruning, and CyberGIS-BioScope for biomass transportation planning at the tactical level. At operational level, however, only Malladi et al. (2018) developed an Excel-based DSS for forest-based biomass transportation and Mirowski et al. (2014) looked at the usage of Information and Communication Technologies (ICT) in forest supply chains tested on a case study in Australia, which used a DSS named FastTRUCK.

Ten papers used multi criteria decision-making methods (MCDM), including analytical hierarchy process (AHP) (e.g., Galvez et al. (2015)), the best-worst method (Rahemi et al., 2020), goal programming (e.g., Hashemi-Amiri et al. (2023)), the multi-objective best fit strategy (Kogler and Rauch, 2020), and Ɛ-constraint methods (e.g., López-Molina et al. (2020)). Although not as common as exact methods, researchers have also provided (Meta)heuristic algorithms (18 papers), which are, in most cases, applied to deal with complex problems at the operational level.

Fig. 11 depicts a breakdown of papers based on their modeling assumptions. It can be observed that the upstream biomass transportation is mainly carried out by road transportation (84 %) with full-truck-loads (90 %). Dominant assumptions include a network supply chain configuration (76 %) using deterministic data (81 %) over a single planning period (71 %) without time windows (96 %). While 91 % of studies focused on a single biomass sector (Fig. 5 (left)), the category "Number of feedstocks" was well balanced between the single and multiple feedstocks.

As previously discussed, our primary focus is on reviewing the upstream transportation of biomass, though 30 % of the reviewed papers studied the downstream transportation as well. Consistent with the findings of Ko et al. (2018), trucks are identified as the dominant mode for biomass transportation (84 %); primarily used as a single mode (62 %) but also as part of a multimodal system (22 %). Given the high

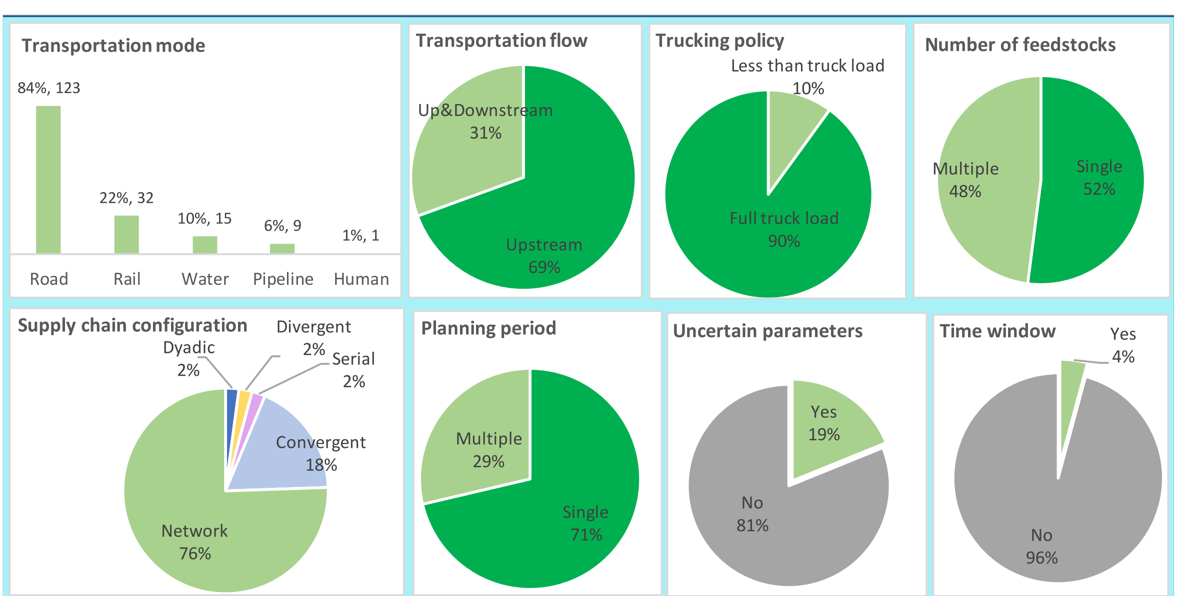

Fig. 11. Distribution of modeling assumptions in the reviewed papers.

volume typically involved in biomass transportation, full-truck-load (FTL) policies are more common, except in 10 % of the papers, which focus on less-than-truck-load (LTL), mainly in studies considering urban waste collection (6 studies). In multimodal transportation, trucks are usually used to transport feedstock to terminals and/or ports. Some papers exclusively used waterways (Mafakheri et al., 2021) or trains (Flodén and Williamsson, 2016; Ko et al., 2020; Palander, 2015) for transportation planning from port to port rather than for the entire stream. Pipelines are discussed in nine papers (6 %) for the transportation of substances such as hydrogen (Muresan et al., 2013), natural gas (Pantaleo et al., 2014), and CO2 (Li et al., 2020). For example, Isafiade et al. (2022) integrated the periodic heat demand of sets of co-located process plants with a biomass-based utility supply chain network. A network of rail and road link biomass supply nodes in the supply chain to the central utility hub, while a pipe network links the utility hub to a set of co-located process plants for process streams transportation. Finally, Tucho et al. (2016) looked at a remote rural area in Africa, where firewood is transported by women who are responsible for household chores, using head-loading and back-loading from forest to the households.

Montoya-Torres and Ortiz-Vargas (2014) classified supply chain configurations into five categories: serial, dyadic, divergent, convergent, and network. In a serial configuration, supplier, manufacturer, distributor, and retailer are considered. Dyadic configuration represents a supply chain with a single supplier and a single customer. A divergent configuration connects one supplier to multiple customers, while a convergent structure connects multiple suppliers to one customer. Finally, a network configuration is the combination of divergent and convergent structures. The biomass supply chain was assumed more in network or convergent configuration (Fig. 11). We expected these assumptions because biomass transportation typically involves a large volume of biomass transportation from multiple supply nodes to either multiple energy plants (network) or to a single plant (convergent). 81 % of the studies assumed deterministic data. Consideration of multiple types of feedstock –like switchgrass, corn stalk, and wheat straw– can increase biomass supply, mitigate the seasonality caused by the non-harvesting seasons, and consequently, assure smoother bioenergy production with higher unit profit (Zhu and Yao, 2011). This captured the attention of the reviewed papers (48 %).

3.2.1. *Critical discussion*

Here, we discuss the main findings for RQ1 and highlight promising research avenues. Biomass is characterized by its low energy density (Mobini et al., 2014), which indicates the need for large volumes of feedstock for bioenergy production. Some researchers mentioned utilization of multimodal transportation for handling transportation of large volumes more efficiently, which we will discuss in more detail in RQ2 as an EM. Here, we discuss the impact of optimal utilization of multiple types of feedstock on reducing the transportation costs associated with handling these large volumes. Using various local feedstocks instead of relying solely on one type from long distances can both decrease transportation distances and mitigate the seasonality caused by non-harvesting seasons. Although 48 % (70) of the reviewed papers considered multiple types of feedstock, only 13 of them studied the utilization of biomass from two or three sectors of forest, Ag, and MW (see Fig. 5, left). Among these, no paper was at the operational transportation planning level, and this could certainly be a future research direction. We think the lack of studies on this matter is likely due to a focus on solving real-world problems, which did not consider supply of biomass from multiple sectors. Another reason might be that vehicle routing problems are inherently complex, and the inclusion of biomass from multiple sectors adds further complexity. This arises not only from the different types of biomass but also from the need for a larger fleet of heterogeneous trucks from various transportation companies, potentially increasing transportation costs. Authors might have tried to avoid such extra cost and complexity. However, incorporating an appropriate structure or mechanism could mitigate these increased costs and achieve greater reductions.

Overall, compared to the tactical level, the operational level of biomass transportation planning has received less attention in the literature (Malladi and Sowlati, 2017, 2018). Despite our effort to cover all relevant papers at this decision-making level by tracing the citations of the papers found using keyword search and by including some papers from forest and MW sectors that discuss transportation EMs, we found hardly 30 papers. This number is about half of those found in either tactical or strategic levels. Among these, only 15 papers addressed the transportation of biomass for the purpose of bioenergy production, while two of these, (Isafiade et al., 2022; Khaloie et al., 2021), did not focus on operational transportation planning, but operational production planning.

In the forest sector, three studies concentrated on vehicle routing, while four papers studied vehicle scheduling. Soares et al. (2019) addressed the full truck-load pickup and delivery problem, focusing on multiple vehicle synchronization, including truck, lorry, and loader, for the simultaneous chipping and transportation of forestry biomass. Zamar et al. (2017) studied a stochastic VRP for collection of sawmill residue from several sawmills to a single depot to be used as an energy source in the pulp mills. Malladi et al. (2018) developed a transshipment model to determine chipping schedules and the number of truckloads of each forest biomass type to be transported each day with different types of truck. They also proposed a routing model, which uses the results of the transshipment model, to determine the optimal routing for the available trucks for a large biomass logistics company in British Columbia, Canada.

Eliasson et al. (2017) developed a discrete event simulation model for scheduling chipper, forwarder, and truck operations, which included chipping logging residues at the landing, forwarding them to a reloading point, and transporting them to a heating plant. Pinho et al. (2015) implemented Model Predictive Controllers in forest biomass supply chain management, coordinating the chipping and transportation of the chips to the power plants by trucks to assure timely response to disturbances. Marques et al. (2018) developed a MILP model for optimal allocation of wood chips at forest sites to terminals and power plants, synchronizing chipping and transportation at the roadside. Han and Murphy (2012) addressed a truck scheduling problem for transporting four types of woody biomass (chips, hog fuel, sawdust, or shavings), in western Oregon, from sawmills to conversion plants (energy or pulp) or harbors for export.

Regarding the agriculture sector, An (2019) provided a MILP model for a truck loader routing and scheduling problem that considered multiple trips and visits, along with synchronized loading operations at satellite storage locations for transportation of corn stover bales. An (2022) extended this model to consider open routing for loader and closed-routing for truck. Gracia et al. (2014) applied a classical VRP to biomass collection problem using a fleet of several agricultural vehicles, including chippers, trucks, tipper trailers, and tractors. A hybrid approach based on genetic algorithms and local search methods was presented to solve a real case study in Spain. Panyoyai and Rangsri (2013) relaxed the traveling salesman problem to minimize the cost of a power plant picking up agricultural waste from several supply sites. They also created another model to decide whether the power plant would have to pick up the waste, or whether the suppliers should deliver the waste to the power plant in order to minimize the overall transportation cost in the biomass logistics system.

Regarding the MW sector, Hashemi-Amiri et al. (2023) studied an integrated smart waste management framework and developed a novel multi-objective model for integrating resource allocation and VRPs considering multiple types of waste and a heterogeneous fleet from different separation centers to collect a waste container throughout the city. Galvez et al. (2015) integrated MILP optimization and AHP to address a biogas facility location problem and its associated reverse logistics network considering multiple types of municipal waste in

Greater Nancy, France. Shi et al. (2023) proposed an optimization model for a multi-depot collaboration routing location problem with pickup and delivery for designing a circular symbiosis network.

Therefore, operational level planning of biomass transshipment, integrating truck routing and scheduling while considering biomass from multiple sectors using different truck configuration, can be the focus of future research. Only Malladi et al. (2018), Hashemi-Amiri et al. (2023), and Han and Murphy (2012) considered multiple types of feedstock within the same sector using a heterogenous fleet of trucks. Moreover, as Sarbijan and Behnamian (2023) introduced as an emerging area of VRPs, real-time VRPs in biomass supply chain where demand is generated dynamically over the operational time horizon without prior knowledge can be another research direction. Development of DSSs specifically for biomass transportation at the operational level is also another area of interest for future research. To the best of our knowledge, Malladi et al. (2018) is the only study providing an Excel-based DSS for this matter. More research needs to be conducted investigating appropriate metaheuristic approaches to solve complex VRPs for real-world biomass case studies. According to the review of Audy et al. (2023) on solution methodologies provided for routing and transportation in general forestry, a wide variety of exact and heuristics methods, such as column generation, branch-and-price, greedy heuristic with a Tabu component and constraint programming model, Tabu Search, simulated annealing, and ant colony optimization, and several hybrid multi-phase approaches are proposed. However, they all are used for solving log truck routing, and none of them are in biomass transportation planning.

Finally, we highlight consideration of uncertainty factors in the provided transportation models. Audy et al. (2023) mentioned that various types of information uncertainty might occur at the operational planning level, such as supply volumes, traveling, queuing, and waiting times. These changes might be due to a new customer order which arrives, supply amount changes, an unforeseen event that occurs, vehicles break down, and traffic delays. Our research revealed that only 19 % (27) of our reviewed papers considered data variations. Among these six papers did not considered energy production while five papers considered dynamic data rather than uncertain data. The rest of them considered uncertainty factors in parameters like biomass supply, demand, and cost. This research direction is also highlighted by Malladi and Sowlati (2017). Consideration of time window constraints at operational biomass transportation planning could also gain to be pushed forward as only 4 % of the studies considered either soft or hard time window constraints. We think that this matter is overlooked by the authors as two forms of time window constraints at supply or demand sites of forest industry can exist: opening hours and on-site loader operating hours. Vehicles arriving before the hard time window(s) or outside the loader operating hours can cause long waiting and queuing times (Audy et al., 2023). This issue likely applies to other biomass sectors as well.

3.3. Mechanisms used by the articles (RQ2)

The second research question addressed the mechanisms used in the literature to enhance the efficiency of transportation planning. The reviewed papers used various terms such as collaboration, coordination, cooperation, and integration when referring to these mechanisms. However, we found that these terms were often used interchangeably without clear boundaries distinguishing them. Therefore, we decided to refer to all these as Efficiency Mechanisms (EMs), which means any strategies and technologies designed to optimize resource utilization, reduce costs, and minimize environmental impacts, thereby enhancing the overall sustainability of the transportation network. We identified seven main EMs, as shown in the interior circle of Fig. 12, each with subcategories depicted in the outer ring in the same color. The main EMs include resource sharing, multimodal integration, joint decision making, transit preparation, financial agreement, information sharing, and local feedstock integration. It is important to note that some papers studied more than one EM.

Resource sharing. Resource sharing is the most common category,

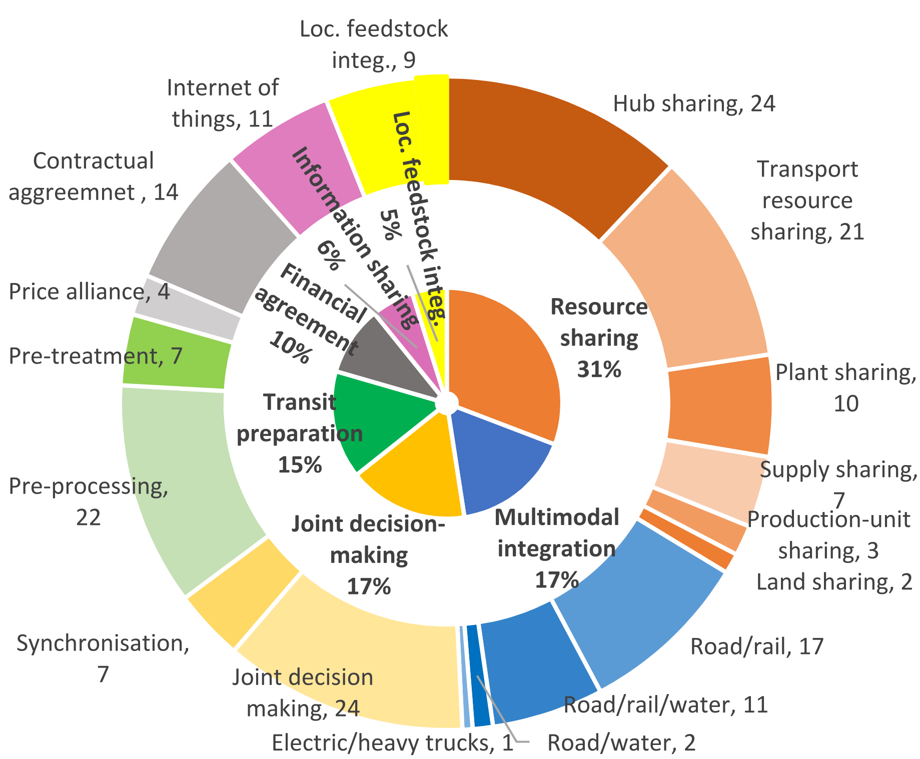

Fig. 12. Efficiency mechanisms (EM) identified in the literature. The interior circle shows the main EMs, and the exterior ring shows the subcategories of each main EM, using the same color for easy identification. (Loc feedstock integ.: Local feedstock integration). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

appearing in 31 % (57) of the studies. It refers to the members of the same supply chain or multiple supply chains sharing their assets to make transportation more efficient and to reduce costs. Under this class, we identified the following six subcategories: hub sharing, transport resource sharing, plant sharing, supply sharing, production unit sharing, and land sharing.

The strategy of hub sharing is commonly used in biomass transportation planning, studied by 24 out of 57 of the papers. Hub sharing involves multiple suppliers sharing intermediate storage/satellite yards (referred to as hubs or terminals) for temporarily storing the collected feedstock. These terminals are also used for transloading (changing transportation modes) or upgrading the feedstocks (e.g., comminution, drying) before their final long transportation to conversion facilities (Fernandez-Lacruz et al., 2019).

The strategy of transportation resource sharing is a well-known approach aimed at reducing transportation costs. Out of 57 papers, 21 of them used this strategy, making it the second largest subcategory. This strategy was mainly studied under two concepts: backhauling and bartering, which are well-defined by Frisk et al. (2010) and Guajardo et al. (2018a). Bartering enables companies to exchange tasks, fulfilling demand points from each other's supply points. This means that two collaborating companies can use all of each other's supply areas as a common resource to reduce the total traveling distance (Audy et al., 2012a). Backhauling combines supply and demand points of different companies in a shared route, discovering more efficient routes with reduced empty running. 15 out of 21 papers used backhauling and/or bartering, both of which reduced the empty miles covered by transporting trucks. It should be noted that there are some examples (6 out of 21 papers) of transportation resource sharing that do not refer to backhauling or bartering concepts. Shastri et al. (2011) described the share of trucks for all transportation operations within the same supply chain. Flodén and Williamsson (2016) aimed to replace unsustainable road transport of wood fuel with more sustainable intermodal transport, which required large transport volumes. To achieve sufficient volume to fill a train, two heating plants were assumed to collaborate by either using the train on alternate days or routing the train to a location close to both plants. Pantaleo et al. (2014) discussed sharing existing district heating and gas networks with renewable energy to transport the final energy produced.

Plant sharing involves integrating biofuel production into existing infrastructures, such as petroleum refineries (Tong et al., 2014), sawmill sites (Ahlström et al., 2017), combined heat and power plants (Leduc et al., 2010), coal-fired power generation facilities (Idris et al., 2018), etc. This subcategory was discussed in 10 out of 57 papers.

Supply sharing is an agreement among multiple biomass customers to share the total volume of the available biomass supply among themselves based on the amount of their needs. This subcategory contains seven papers. As an example, Shu et al. (2017) discussed two competitive bioenergy plants -a biorefinery and a biomass base power plant-competing for limited bioenergy feedstock and good sites. This competition affected the types of good transported as well as transportation distances and volumes. Mullins et al. (2014) also studied the optimal allocation of cellulosic biomass feedstocks to three competing energy end users -heating, transportation, and electricity.

The strategy of production unit sharing was discussed in three papers, which explored how centralized and decentralized facilities can help reduce transportation costs. Alarcon-Gerbier et al. (2023) studied a decentralized mobile and modular recycling network, focusing on dynamic multi-period facility location and VRP models. They relocated mobile recycling units from site to site according to waste generation and market demand for recycled products in each period to minimize transportation, recycling, and facility relocation costs. Mitropoulos et al. (2009) developed a dynamic facility location problem for an integrated solid waste management system to minimize the overall costs. They proposed selecting central permanent locations for treatment plants and transfer stations, while temporary landfills should be located and relocated based on dynamic changes and limited capacity. Golberg et al. (2012) discussed an integrated solar-biomass biorefinery designed to meet the transportation fuel demand of a town in India.

The concept of land sharing was discussed in two papers: (Rahemi et al., 2020; Shi et al., 2019). They focused on the practice of sharing cropland for growing both food crops and biomass feedstocks for the production of food and bioenergy products. Although it may not seem to directly reduce transportation costs, utilizing local lands for biomass cultivation and food crops eliminates the need for transporting biomass over long distances, thus reducing significant delivery costs. Shi et al. (2019) introduced oilseeds to existing crop rotations for coproduction of food and renewable jet fuel. This system was predicted to increase farmer net incomes, improve fertilizer use efficiency, and decrease life cycle GHG emissions as well as fossil energy demand compared to fossil jet fuel.

Multimodal Integration. Multimodal integration is an EM used for long-distance transportation and examined in 17 % of the reviewed studies. As discussed earlier, trucks meet the requirements of 84 % of the reviewed papers as a single mode. Rail and waterway transport have a lower variable cost per km and a lower environmental impact than road freight, but they suffer from limited accessibility, high fixed costs, and specific infrastructure needs such as specialized terminals, dedicated infrastructure, and transload facilities/equipment (Flodén and Williamsson, 2016).

According to Flodén and Williamsson (2016), combined road/rail transportation is the most sustainable multimodal transport option for biomass when considering all three cost factors -economic, societal, and environmental. Shi et al. (2019) used The Alternative Fuel Transportation Optimization Tool (AFTOT) model to identify the optimal transportation modes for moving oilseed from local storage to biorefinery and transporting the produced hydrotreated renewable jet (HRJ) fuels to end users. Transportation through road and rail were optimally selected, resulting in both economic and environmental benefits. Combined road/rail/waterway transportation is the second most sustainable multimodal system, followed by combined road/waterway transportation. Ships, barges, or water transport, which can be used both for inland shipment and between countries, have received less attention. Yun et al. (2020) performed a techno-economic evaluation of five possible process configurations for the production of conventional and torrefied (roasted) wood pellets in the Canadian province of British Columbia. They transport wood pellets by trucks to nearby railhead at Prince George, then marine shipping is used to transport them to overseas markets (Japan and the UK) and rail is used to transport them to domestic markets (Alberta and Ontario). Comparing rail and ship transport, they proved that waterway transportation is much cheaper than rail over the same distance. Rhoma et al. (2011) conducted a case study in Duisburg City, Germany, where the entire waste from 46 districts is collected daily using different collection vehicles. Then, it is transported to an incineration plant in the country by ship owing to the presence of ports on either side of the river Rhine. Compared to the truck, the large transshipment capacity by ship not only reduced distances but also reduced $CO2$ emission and reduces road traffic.

Another alternative is combined electric/heavy trucks. Zhang et al. (2022) conducted a case study for the co-processing of bio-oil and vacuum gas oil in Henan Province, China. The study suggested that the optimal transportation mode between the collection site and the storage site was electric truck while the optimal one between the storage site and co-processing site was heavy truck.

Joint Decision-Making. Joint Decision-Making is an important topic in supply chain management, with 17 % of papers discussing it. This concept involves two or more supply chain actors jointly making decisions based on their needs. For instance, a supplier and a customer might jointly decide on the volume of supply and the time of delivery. Synchronization is a specific type of joint decision-making, where a planning-support system is developed to share the information and synchronize the decisions. Seven papers specifically studied synchronization. For example, in a study by Soares et al. (2019), simultaneous chipping and transportation of forest biomass were examined using operational synchronization between a truck and a loader to load the trucks by the loader in a queue, reducing unproductive waiting times. The loader was also supported by a lorry using a movement synchronization. The lorry picked up the loader and dropped it off between the biomass pickup location.

Transit Preparation. Transit preparation is the additional step taken in the biomass supply chain compared to the roundwood supply chain. It involves converting biomass into smaller and more densified material through pre-processing or pre-treatment operations at harvest sites or terminals, before final transportation to the industry. This enables more energy content to be transported per trip and reduces transportation costs, particularly for long distances (Mobini et al., 2014). Pre-processing involves making smaller particles or fragments using a chipper, grinder, shredder, hammer, or other equipment through comminution operations (Paulson et al., 2019), as well as drying, baling operations, or densification using a solid waste compactor (Womac et al., 2017). Pre-treatment involves technologies that can create higher value-added energy-densified feedstock, such as torrefaction (roasting), briquetting, gasification, palletization, and hydrothermal liquefaction (Idris et al., 2018; Paulson et al., 2019). 15 % of the studies covered this EM, as indicated in Fig. 12. For example, Paulson et al. (2019) studied the logistics effects of the location for two operations, including Biomass Conversion Technology (BCT) as pre-treatment operations and Centralized Biomass Recovery Operation (CBRO) as preprocess operations. The findings suggested that arranging the two to occur at the same in-wood site resulted in shorter travel time compared to separate in-wood sites.

Financial Agreement. Financial agreements were the focus of 10 % of the studies and they encompassed two subcategories: price alliance (4 papers) and contractual agreement (14 papers). Price alliance involves negotiations on pricing to enhance the profit of the allied enterprises. Sun et al. (2011) conducted a feasibility analysis for biomass-coal power plants in China, which would choose coal when the coal price is relatively low and would turn to the biomass resource when the coal price increases. A game model was proposed to determine the interactions between factors including unit procurement cost, unit transportation cost, basic price, and coal price for crop residue collection. Then, a Monte Carlo simulation was implemented to compare the collector's and power plants' profit increase under each game when the supplier forms an alliance with one power plant or with all power plants. Contractual agreement refers to formal and informal contracts between supply chain members such as farmers, bioenergy plants, end users, and transportation providers. These contracts are typically agreed upon for a certain period during which members are responsible for their terms (Ebadian et al., 2014). For instance, Liu et al. (2018) explored government subsidy mechanisms provided to farmers and bio-energy plants as an external motivation for straw-based bio-electricity production.

Information Sharing. In the context of supply chain collaboration, Audy et al. (2012b) noted that different levels of information may be exchanged between collaborating actors, depending on their relationship type. When jointly deciding on operations, actors exchange strategic information such as customer demand, forecasts, and operational capacities. This type of collaboration is covering under "joint decision-making" EM. On the other hand, the exchange of transactional information such as orders, payments, delivery confirmations, etc. is categorized under the "information sharing" EM. It was observed that Internet of Things (IoT) devices are repeatedly used to share transactional information, integrating the cyber environment for better decision-making support. 11 of the reviewed papers explored how IoT devices are employed to trace transportation operations and support improved transportation planning.

Local Feedstock Integration. Local feedstock integration is an EM used at the strategic level. It involves the introduction of new feedstock into the supply chain (Mupondwa et al., 2018) or the decentralization of bioenergy plants to keep smaller transportation radius (Woo et al., 2018, 2020). Only nine of the reviewed papers studied this EM. Mupondwa et al. (2018) evaluated the commercial potential of introducing triticale as an energy crop in the Brown agroecological soil zone of the Canadian Prairies. The idea was to integrate the use of triticale grain and straw so as to advance the triticale biorefinery in a rural western Canadian region for ethanol production. Results showed that Ethanol selling price, plant capacity, and feedstock cost highly impacted the net present value.

3.3.1. *Critical discussion*

In this section, we will discuss the trends and future research directions concerning the EMs used in the literature to improve transportation planning. Operational-level biomass transportation planning is not only studied in a limited manner, but the implementation of the EMs to enhance this level of transportation also seem very limited. Out of the 30 papers at this level, five did not incorporate any of the identified EMs, including (Galvez et al., 2015; Gracia et al., 2014; Simard et al., 2023; Xue and Cao, 2016; Zamar et al., 2017). Simard et al. (2023) focused on operational level production planning rather than transportation planning, unlike the other four.

Studies such as (Flisberg et al., 2015; Guajardo, 2018), respectively, mentioned the possibility of reducing transportation costs and emissions by 5–15 % and 11–54 % through bartering and backhauling, under the "transportation resource sharing" EM. However, only nine out of the 21 papers that studied this EM focused on biomass transportation, mainly providing tactical level planning. The remaining papers focused on planning transportation of other products to mills, such as pulp & paper mills.

In studies on biomass transportation at the tactical level, several researchers explored the "transportation resource sharing" EM to improve efficiency. Flodén and Williamsson (2016) examined the efficiency of sharing a train between two heating plants. Shastri et al. (2011) proposed sharing trucks for all transportation operations within the same supply chain. Kärhä et al. (2011) discussed integrating pulpwood and energy wood procurement using whole-tree bundling, and separated the bundles into pulpwood and energy wood fractions upon arrival at the debarking drum. Pantaleo et al. (2014) performed techno-economic analysis for the integration of bioenergy routes into existing energy infrastructures and networks. Additionally (Abasian et al., 2017; Flisberg et al., 2015; Guajardo et al., 2018a, 2018b), explored the use of backhauling and bartering to improve biomass transportation planning.

"Transportation resource sharing" at the operational level for biomass transportation, however, was only studied by Guajardo (2018). They developed a collaborative asymmetric VRP with wood bartering and backhauling routes for forest biomass transportation, considering multiple depots and a homogenous fleet of trucks. They provided a game theory method to quantify and allocate greenhouse gas emissions among the coalition members. Three other studies, including (Han and Murphy, 2012; Hashemi-Amiri et al., 2023; Malladi et al., 2018), used a heterogeneous fleet of trucks for the transportation of multiple types of feedstock and improved transportation efficiency through "transit preparation: Pre-processing", "information sharing: IoT", and "financial agreement: contractual agreement" EMs. They all considered supply biomass from one sector: forest or MW, and their models did not allow truck sharing while considering biomass type and truck type compatibilities. Malladi et al. (2018) considered this compatibility, but no truck sharing was considered. Different truck configurations mean that different types of truck are used for different assortments, which cannot be used interchangeably, such as logging trucks used for roundwood and chip van trucks used for chips transportation.

There are two studies on improving this level of transportation through "transportation resource sharing" EM although for transportation of other products in forest and MW sectors. Marques et al. (2020) integrated inbound and outbound logistics of a wood-based panel industry in Portugal, using a VRP with backhauls. A heterogeneous fleet of trucks was used for the supply of chips in linehaul routes and delivery of wood boards in backhaul routes when it was cost-effective. Gruler et al. (2017) provided a collaborative VRP for urban waste collection problems with multiple depots and a stochastic demand. A capacitated fleet of vehicles from different depots, which served as waste collection companies, were shared to collect wastes throughout the collection area under a less-than-truck-load (LTL) policy. These studies provided VRPs for a single-product transportation.

These existing VRPs, however, may need modifications to be applicable to real-world biomass transportation with different truck configurations and multiple biomass types because biomass transportation typically involves multiple feedstock types either from single or multiple sectors, which are transported by different truck types with full-truck-load (FTL) policy. The main obstacles and difficulties to practical implementation of these EMs are the development of DSSs to support them, as discussed by Basso et al. (2019) who reviewed obstacles to horizontal collaboration implementation in logistics. Additional issues, such as the need for sensitive information sharing with competitors (Audy et al., 2012b) and the risk of sharing incorrect information, also hinder the practical implementation of EMs. Some actions can address such information security and confidentially barriers: standardization of information flow, using dedicated platforms, signing contracts, and involving a third party (Audy et al., 2012b). Moreover, we believe that organizations should take the advantage of IoT devices, for the sake of biomass transportation, especially in operational level truck routings, and benefit from analysing real-time big data. Among the three reviewed papers, which used IoT at the operational level, only Hashemi-Amiri et al. (2023) used it in a VRP model for biomass transportation planning.

3.4. Measurement metrics for the performance of the proposed planning (RQ3)

This section addresses the third research question about the metrics used to measure the performance of the proposed methodologies and EMs in terms of the three dimensions of sustainability: economic, environmental, and social. It was observed that the measuring metrics were examined following three different strategies. In the first strategy, authors considered the metrics as part of the objective function for the proposed methodology (this was used for economic, environmental, and social objectives by 138, 35, and 13 papers, respectively). In the second strategy, authors calculated the economic, environmental, and social impacts of the planning using an equation outside of the mathematical model. In the third strategy, the authors explained the impacts without quantifying them (this is covered by 3, 12, and 5 papers, respectively). Fig. 13 depicts the key points regarding the measurement metrics considered in all reviewed papers, regardless of the strategy used. More than half of the papers (57 %) aimed to reduce monetary cost, which are referred as economic objectives, followed by a quarter (26 %) considering both economic and environmental objectives. Additionally, 11 % of the papers considered all three dimensions of sustainability.

The two pie charts in Fig. 13 show the percentage of the papers based on both their number of objectives and their dimensions of sustainability. A single objective can consist of only one dimension of sustainability (like Ec), or be a weighted sum of more than one dimension. This can be seen when comparing the two pie charts. Three-quarters of them optimized a single objective, and half of these aimed to minimize the unit cost. The remaining quarter considered more than a single objective; 11 % had bi-objective functions and 14 % had three or more objective functions. The specific objective functions in each dimension of sustainability are illustrated in Fig. 13. The analysis highlights that economic objectives were the primary focus, with 138 studies addressing them in total. Unit cost was the most frequently considered metric, appearing in 56 % of the papers. Other metrics were less frequently examined, including profit (12 %), travel time (8 %), net present value (7 %), and distance (6 %). Additionally, a combined 14 % of studies considered other economic objectives such as economic efficiency, volume fulfillment, the number of transportation resources, payback periods, internal rates of return, profitability indices, revenue, queuing times, and order splitting values.

Environmental objectives were considered significantly less frequently, with 35 papers addressing them in total. Among these, the most common metric was the minimization of GHG (Greenhouse Gas) emissions, included in 16 % of the papers. Energy efficiency was the next most common, considered in 3 % of the papers. Other environmental factors such as safety, negative impact on the environment, and cropland suitability were each considered in fewer than 2 % of the papers.

Social objectives were the least frequently examined, with only 13 papers considering them. Among these, three papers focused on maximizing social welfare. Safety and resident satisfaction were each maximized in two papers. Other social factors, including side effects on society, job creation, and population exposure, were considered in one paper each.

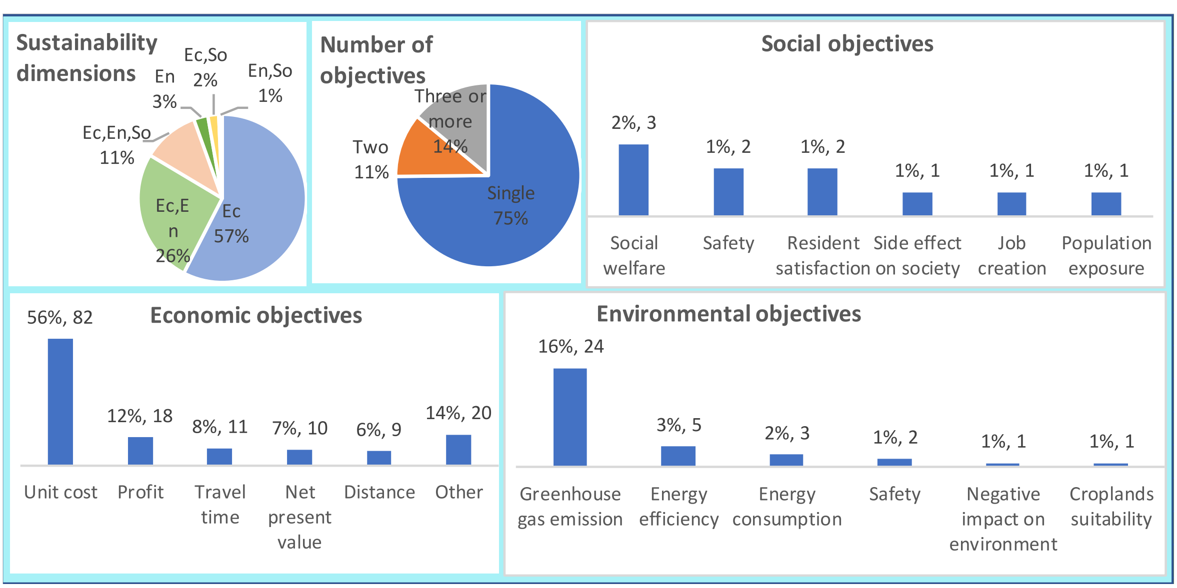

Fig. 13. Percentage of papers regarding their sustainability dimensions, number of objectives, and the specific objective functions: Ec: Economic; En: Environment; So: Social.

Another topic considered in the literature is that when the improvement through the application of the EMs is measured using these metrics, it is necessary to allocate the benefits among the involved stakeholders (Frisk et al., 2010). Among the studies that we reviewed, 19 papers provided such allocation methods. They used several methods to allocate the saved costs (Audy et al., 2012a; D'Amours and Rönnqvist, 2013; Flisberg et al., 2015, 2018; Frisk et al., 2010; Guajardo et al., 2016; Guajardo and Rönnqvist, 2015; Rönnqvist et al., 2018), profits (Alcocer-Garcia et al., 2022; Audy et al., 2012a; Basso et al., 2021; Gao et al., 2019; Khaloie et al., 2021; Liu and Liao, 2021; Sampat et al., 2019; Tominac et al., 2022; Wang et al., 2022), or environmental emissions (Guajardo, 2018) among the stakeholders. The methods included cooperative game theory (Frisk et al., 2010), Stackelberg game theory (Wang et al., 2022), independent system operator (ISO) (Sampat et al., 2019), and altruistic and opportunistic behavior of the leading company (Audy et al., 2012a). Cooperative game theory was the most frequent method used by 14 papers.

3.4.1. *Critical discussion*

In this section, we will summarize the key findings for the third research question. Consistent with the findings of Ko et al. (2018) and Malladi and Sowlati (2018), we discovered that the majority of the studies concentrated their effort on economic objectives. As a result, there have been limited explorations of combining the three cost factors (economic, environmental, and social factor) to estimate sustainable transportation costs. Among the papers reviewed, only four incorporated the three factors in their objective functions: (Deng et al., 2023; Islam et al., 2023; Miret et al., 2015; Woo et al., 2018), and their primary focus was on the network design (facility location-allocation and/or biomass availability assessment problems).

The biomass sector has been the focus of a few studies on cost savings and greenhouse gas emission allocations. Specifically, Flisberg et al. (2015) and Guajardo (2018) looked at the allocation of cost savings and emission savings gained from "transportation resource sharing" at tactical and operational levels. Furthermore, Alcocer-Garcia et al. (2022), Tominac et al. (2022), and Wang et al. (2022) studied profit allocation gained from "financial agreement" EM. Gao et al. (2019) and Khaloie et al. (2021) investigated profit allocation gained from "joint decision making" EM. Mafakheri et al. (2021) also theoretically explained that cooperation through "hub sharing" EM benefits the involved communities. However, these studies primarily focused on tactical-level transportation planning, with Khaloie et al. (2021) being an exception and addressing operational-level production planning, and Guajardo (2018) addressing the operational-level biomass transportation planning problem with a focus on emission allocation. Quantification and allocation of the benefits gained from the remaining EMs would worth to be studied more thoroughly as well.

At this point, with all three research questions comprehensively addressed, we illustrate an efficient biomass transportation mechanism in Fig. 14 to demonstrate how this mechanism works for better managing the transportation of biomass in the supply chain. Here, we give an example of "transportation resource sharing", which is a specific type of the broader "resource sharing" EM shown in Fig. 12. In this example, trucks—typically used to transport biomass in full truckloads—serve as the shared transportation resource. Fig. 14(A) presents three dedicated truck routes: one for crop residue, another for wood chips, and a third for municipal waste (waste wood and waste wood chips), each assigned to the agriculture, forest, and municipal waste sectors, respectively. The solid and dashed arcs represent loaded and empty truck movements, respectively. As shown, fulfilling full truckload requests within each sector independently often results in trucks traveling long distances empty to reach their next pickup location. However, when trucks are shared across the three sectors, as illustrated in Fig. 14(B), empty trips are shortened, and the overall routing distances are reduced. Truck sharing allows, for instance, the crop-residue truck to transport biomass from any sector along its route, rather than being restricted to delivering only crop residue within the agriculture sector. This flexibility means that instead of a sequence like "crop residue → crop residue → crop residue," the truck can transport "crop residue → crop residue → wood chips," optimizing transportation efficiency and reducing unnecessary empty travel.

4. Discussion

More than twenty years ago, the start of industrial forest fuel utilization led researchers to concentrate on creating and evaluating suitable supply chains and technologies. Today, with modern systems established, the focus has moved to optimizing processes efficiency (Kühmaier and Erber, 2018). Many researchers have pointed out that several gaps and challenges are hindering a comprehensive understanding of potential EMs.

One of the prevalent challenges involves typical assumptions for

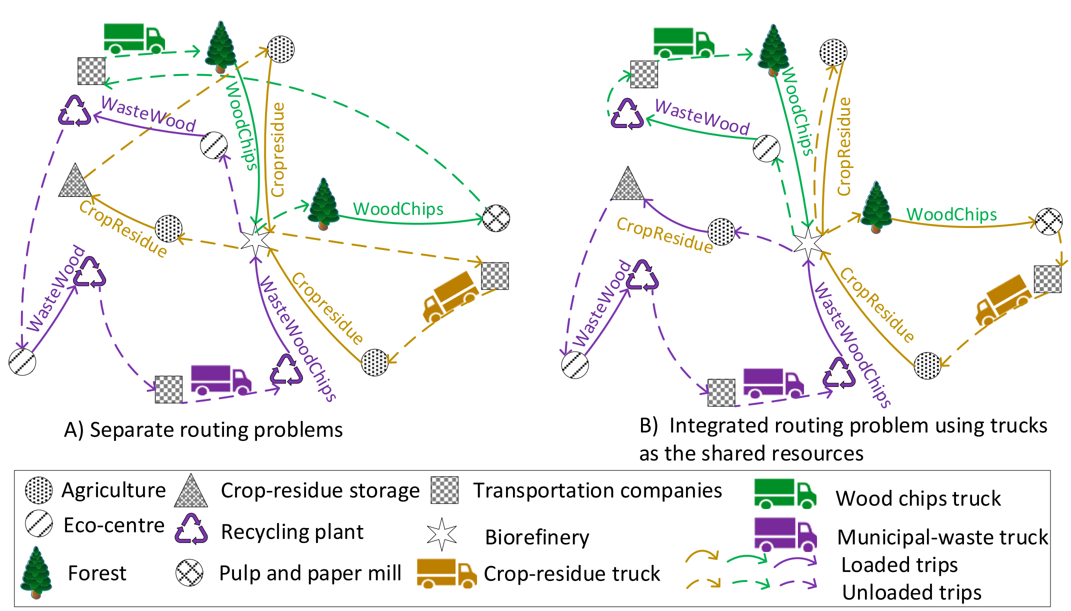

Fig. 14. An example of "resource sharing" EM proposed to better manage biomass transportation.

biomass types and characteristics. Biomass's low energy density, as an instinct characteristic, necessitates large feedstock volumes for bioenergy production. This feature along with others such as spatial fragmentation, high moisture content, and seasonal availability cause uncertainty factors in biomass supply chains and make them significantly sensitive (Hu et al., 2017). For example, seasonal availability, which indicates the harvest of different biomass during certain times of the year, prevents the continuous flow of biomass to meet demand all year long. It seems that using multiple types of local feedstock from multiple sectors instead of an uncertain availability of a single type from a single sector and longer distances could reduce associated transportation costs.

An additional challenge is that operational-level biomass transportation planning has received less attention compared to the tactical level (Malladi and Sowlati, 2017, 2018). This level of transportation planning is even more interesting when the implementation of it is incorporated with an EM to improve it because a simple optimization plan is not enough for the economic viability of biorefineries with the demand of everyday large-volume biomass transportation. Future research should focus on both implementation and improvement of operational planning of biomass transshipment, integrating truck routing and scheduling while considering compatibility between different truck configurations and multiple feedstock types from different biomass sectors. We identified seven EMs, including resource sharing, multimodal integration, joint decision making, transit preparation, financial agreement, information sharing, and local feedstock integration. All of these could be implemented to enhance this level of transportation planning. We specifically emphasized "transportation resource sharing" under the category "resource sharing" because it has been proven quite efficient in tactical-level planning in terms of both economic and social objectives. Also, there is a need to study appropriate allocation methods to allocate the savings among the stakeholders. These allocation methods are very important to be agreed by all of them to make their collaboration long-lasting.

Finally, there is a scarcity of DSSs that can handle all the above-mentioned factors. Budzianowski and Postawa (2016) highlighted that the development of DSSs specifically dedicated to biorefinery systems involving all relevant physical constituents and system boundaries was required to efficiently perform total chain integration, meaning the optimization of energies and materials used in the total biomass chain and the improvement of economic viability and sustainability of biorefineries. Acuna et al. (2019) noted that most DSSs used for biomass supply chains focused on the strategic and tactical levels, rather than the operational level. Many of these DSSs have been created based on modifications of systems initially designed for transporting logs and mill residues. We believe that the development of DSSs specifically for biomass transportation considering one or multiple EMs and the three cost factors are required to improve transportation efficiency and to sustainably estimate its costs. The road map in Fig. 15 shows the challenges and research directions we identified for making operational biomass transportation planning more efficient.

5. Conclusions

Efficient biomass transportation is a key strategy for compensating the high costs associated with biomass conversion into bioenergy, consequently reducing the overall cost of the value chain, as transportation operations constitute a significant portion of these costs. Enhancing transportation operations through optimized resource utilization, reduced unnecessary costs, and minimized environmental impacts can contribute to a more efficient and sustainable transportation network. However, despite its importance, to the best of our knowledge, no comprehensive review has been conducted on the implementation of EMs to improve biomass transportation.

In this article, a systematic literature review on upstream transportation planning for biomass from the forest, agriculture, and MW sectors was proposed, so as to identify the methods, mechanisms, and metrics used to implement efficient transportation. The following research questions were proposed and answered: (1) Which methodologies are used to implement transportation planning in the biomass value chain? (2) What are the mechanisms used to improve transportation planning? (3) What are the key metrics used to measure the performance of the proposed planning, especially from a sustainability point of view? A total of 146 papers published from 2009 to 2023 in English language were selected following the six steps of a systematic literature review method.

Based on the publications identified, we observed that the majority of the articles considered biomass transportation from a single sector by road transportation with full-truck-load policy. These studies mainly provided optimization models at strategic and tactical levels for real-world case studies in either Sweden, Canada, the United States, or China, and solved them using exact solution approaches. The assumptions defined by the authors typically encompassed the network supply chain configuration, deterministic data, a single planning period, and no

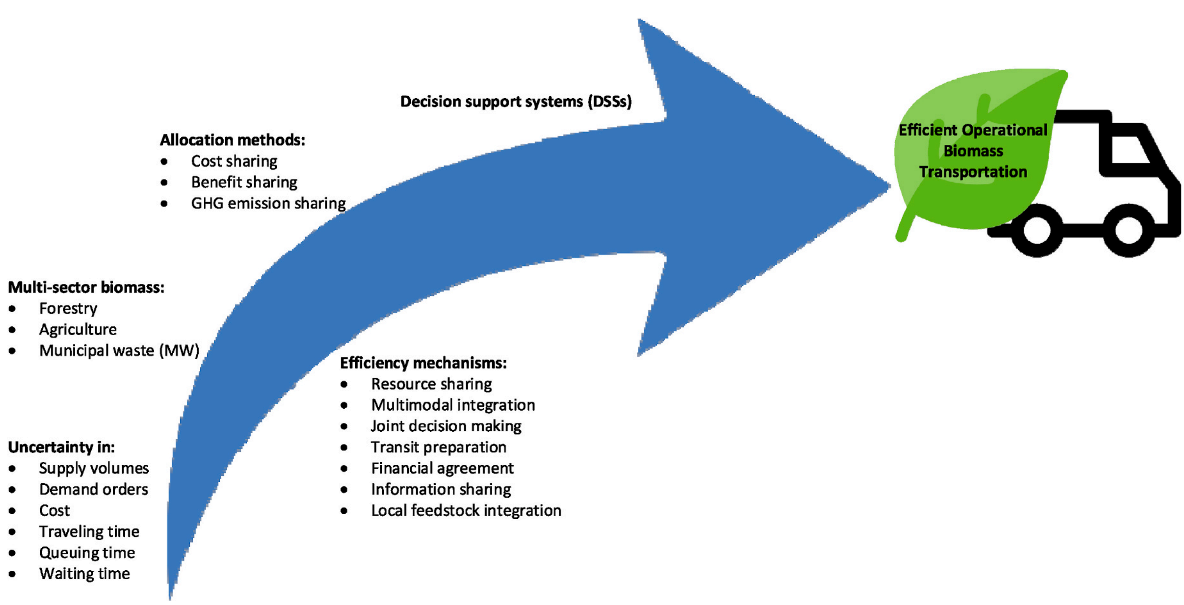

Fig. 15. Future research directions for an efficient operational biomass transportation planning.

time windows. On the other hand, a fairly balanced number of papers assumed single or multiple feedstock types.

We also discovered seven main transportation EMs, including resource sharing, multimodal integration, joint decision making, transit preparation, financial agreement, information sharing, and local feedstock integration. “Resource sharing” was the most frequent EM studied, based on hub sharing, transport resource sharing, plant sharing, supply sharing, production unit sharing, and land sharing. Most of the studies used economic objective functions to quantify the impacts of the proposed mechanisms on the transportation efficiency.

While this paper proposed a comprehensive review, it is important to acknowledge several limitations. The selection criteria for including studies were limited to those with an EM, possibly excluding studies with no EM but valuable insights. Therefore, some methodologies, such as the solution approaches and DSSs identified by (Audy et al., 2023) in the forest sector, were not identified. The research also focused on biomass transportation. Another suggestion would be to review VRP models developed for other industries having full truckload deliveries, e. g., the oil industry, to identify additional EMs applicable to biomass transportation planning at the operational level.

This paper contributes to the field by providing new insights into the methodologies, mechanisms, and metrics used for improving biomass transportation planning at the operational level. Several gaps and challenges were also identified, which are summarized as follows:

- There is a need to improve the biomass transportation planning at the operational level, integrating truck routing and scheduling while considering biomass from multiple sectors transported by different truck configurations being compatible with different feedstock types.
- Operational-level transportation planning with uncertain data or dynamic demand (real-time VRPs) in the biomass supply chain may be an area of interest for future research. IoT devices could be used to collect real-time data to be used for big data analysis and planning improvement as well.
- There is a need to develop a DSS specifically for biomass transportation at the operational level to efficiently perform total chain integration and improve the economic viability and sustainability of biorefineries.
- The “Transportation resource sharing” EM at the operational level of biomass transportation planning can be efficient both in terms of economic and environmental cost savings, and it is worth applying in future studies. The existing VRPs need modifications to be applicable to such a case.
- There is a need to combine all three dimensions of sustainability (economic, environmental, and social) for evaluation of the transportation efficiency. Then, allocation methods should be provided to allocate the cost, emission, and profit savings among the involved stakeholders.

CRediT authorship contribution statement

Asudeh Shahidi: Writing – original draft, Methodology, Investigation. **Mikael Rönnqvist:** Writing – review & editing, Supervision. **Nadia Lehoux:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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