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Review

Integrating bio-hubs in biomass supply chains: Insights from a systematic literature review

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ABSTRACT

Biomass sources are geographically scattered, and seasonal changes influence their availability. Variations in location, type, and feedstock quality impose logistical and storage challenges. Such a dispersion and variety of biomass sources, as well as the dispersion of demand points, may undermine the economies of scale and increase the risk of supply shortage. By consolidating biomass preprocessing and distribution activities in bio-hub facilities, they can contribute to the overall resilience of biomass supply chains (BSCs) and ensure a more sustainable and cost-efficient approach to bioenergy production. As such, investigating the advantages and challenges associated with bio-hub implementation can offer invaluable insights on the efficiency and sustainability of BSCs. Despite its critical role, a major part of the literature on BSCs is confined to the decision-making processes related to biomass suppliers and bioconversion facilities. To bridge this research gap, the current study conducts a systematic literature review on bio-hub implementation within BSCs in the period of the last ten years. Short-listed papers are classified and analyzed meticulously to extract possible improvements from BSC and modeling perspectives. From the BSC viewpoint, one notable gap is the little attention to mid-term and short-term decisions of bio-hub operations such as inventory control, resource management and production planning. Furthermore, the results revealed that environmental and social aspects of bio-hub implementation require considerable attention. From the modeling perspective, findings illustrate the underutilization of integrated approaches to incorporate micro-level and macro-level information in decision-making. In this regard, a number of areas are suggested for further exploration.

1. Introduction

The record levels of CO_2 concentration in the atmosphere, resulting from fossil fuel use, pose a troubling increase in health and environmental risks linked to climate change (IEA, 2022a). In addition, the world is dealing with rarely seen energy security challenges due to conflicts and political instabilities, leading to uncertainties in energy supply and pricing. A solution to these problems is a global shift towards cleaner, renewable energy sources while ensuring affordable and secure energy services. Given this motivation, retrieving valuable resources from waste materials is gaining importance. This practice is essential for building a sustainable and circular economy, preserving ecosystems, and decreasing reliance on finite natural resources (Vitale et al., 2022). Accordingly, the transformation of biomass into bioenergy has attracted significant interest among academics and industries (Zahraeec et al., 2020). Biomass is the primary global renewable energy source, contributing to 55% of the total renewable energy supply (IEA, 2022b). It constituted approximately 10% of the world's overall energy sources in 2019, and it is predicted to double by 2030 (Jazinaninejad et al., 2022). In fact, the wide range of biomass available worldwide renders this form of energy accessible at an affordable price. Bioenergy production includes interconnected processes of biomass sourcing,

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processing, storage, distribution, and conversion, which are known as a biomass supply chain (BSC). As such, realizing the potential growth of bioenergy depends on establishing meticulously devised BSCs that are productive and environmentally conscious (Helal et al., 2023). Fig. 1 illustrates the activities and interconnected relationships between the operations within a generic BSC, where arrows show possible transportation between operations.

Bioenergy can be derived from various feedstock sources, such as agricultural residues, forestry residues, energy crops, and organic waste, which, unlike fossil fuels, are geographically scattered. Some sources of biomass feedstock, such as agricultural residues, may not be accessible all year round or may vary considerably in supply over time (Ekşioğlu and Klein, 2015). The key factors that hold significant importance in biomass utilization for energy purposes, especially forestry residues, are heating value, moisture content, and ash content (Gautam et al., 2017). Heating value signifies the energy released by biomass when it undergoes combustion, while moisture content is defined as the amount of water contained within the feedstock (e.g., wood). Ash content, on the other hand, represents the proportion of inorganic substances found in biomass. These three attributes are interconnected and subject to change over time (Peter, 2002). Hence, the net energy produced by biomass can be influenced by its moisture content because of energy utilization in vaporizing water during combustion (Gautam et al., 2017).

Additionally, the presence of ash in biomass decreases the overall net energy. Consequently, these characteristics can influence biomass procurement costs (Pettersson and Nordfjell, 2007). Furthermore, as the largest contributor to worldwide bioenergy production, the forestry industry presents logistical challenges due to its bulkiness and varying quality characteristics (Gautam et al., 2017). Typically, this results in additional costs for equipment and transportation, potentially leading to increased environmental harm to the environment. Indeed, transporting equipment over long distances solely for feedstock procurement is generally not profitable (Alam et al., 2012). Moreover, access roads constructed within forests often need to be more resistant and deteriorate soon after they are built. Since residual forest biomass is a low-value by-product of the logging industry, it may not be financially justifiable to invest in road improvement exclusively for its procurement. Moreover, weather constraints during certain seasons (e.g., winter) can interrupt transportation operations, while heating demand is typically higher during winter (Gautam et al., 2017). These issues highlight a pressing need to find a feasible solution in establishing and/or scaling up bioenergy production and fostering the sustainable growth and development of the bioenergy sector.

One possible solution to these problems is establishing an intermediary hub between suppliers (e.g., forests) and end users (e.g., biorefineries). A hub acts as an intermediary location where farmers and growers can deliver their by-products (e.g., straw and harvesting residues) for processing into value-added commodities (e.g., dried wood and pellets), which are crucial for bio-based projects (Kulišić et al., 2019). As a result, a variety of biomass types could be consolidated in a single location leading to streamlining the processing and storage activities of feedstock (Nguyen et al., 2020). Bio-hubs offer an opportunity for biomass suppliers to maintain their production during off-season periods and enable companies to connect and trade with one another. Furthermore, these hubs can serve as capital markets for feedstock, providing contractual advantages for stakeholders along the supply chain (Nasso et al., 2020). Therefore, bio-hubs could become a key enabler in facilitating the effective mobilization of bioresources on a large scale. All these endeavors stemming from bio-hub implementation can result in a decrease in seasonal variations in supply and can enhance biomass availability throughout the year (Rai and Monaghan, 2024). Drawing from experiences in Sweden, bio-hubs contribute to the advancement of the bioeconomy despite potential challenges such as increased product demand and the need for infrastructure sharing within hubs. Hence, bio-hub incorporation could help Sweden to reduce its dependence on foreign resources and achieve its target of relying entirely on renewable energy by 2040 (Nasso et al., 2020).

Furthermore, concentrating the transportation operations in one centralized location rather than dispersing them across various supply points, could improve uninterrupted access to feedstock year-round. This is particularly crucial in addressing challenges associated with interruptions in feedstock transportation from fields during certain seasons due to weather restrictions (Gautam et al., 2017, 2022). Moreover, strategically located bio-hubs could offer the opportunity to have access to various transportation modes such as road, rail, and water transport, thus enhancing transportation efficiency (Aboytes-Ojeda et al., 2022b).

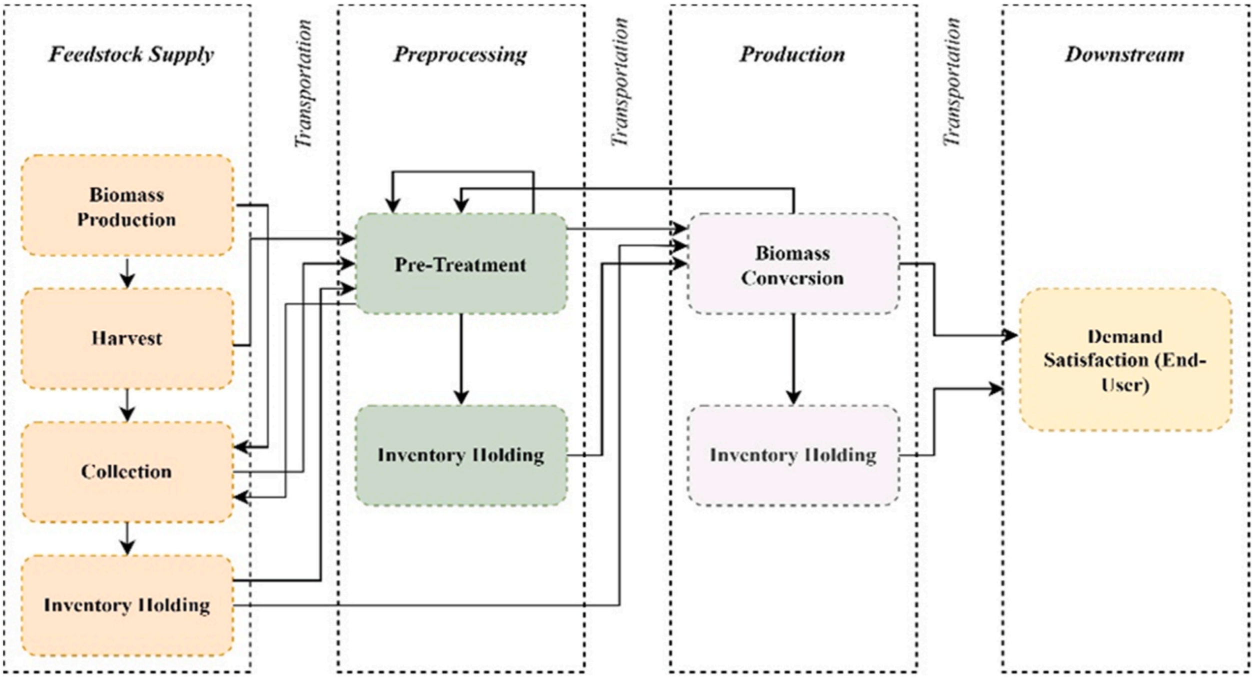

Fig. 1. Activities and operational relationships in BSC (adopted from Jazinaninejad et al., 2022).

As such, bio-hubs play a critical role in achieving a BSC's objective of delivering standardized feedstock to customers in a timely manner and at an affordable price (Kons et al., 2014). Despite its significant advantages, implementing bio-hubs in the context of the BSC presents challenges related to capital investment, operating costs, feedstock availability, and environmental considerations. Hence, careful and comprehensive planning is essential to ensure the successful establishment and operation of bio-hubs within BSCs.

In the BSC literature, researchers have proposed several models aimed at facilitating effective decision-making related to various aspects of actors in a supply chain (SC). There are some interesting review papers in this field, such as the recent works of Zahraeec et al. (2020), Mottaghi et al. (2022), Jazinaninejad et al. (2022), and Habibi et al. (2023). While these papers have delved into BSCs with a focus on sustainability and uncertainty considerations, a notable gap exists in the specific examination of key actors, such as bio-hubs. Therefore, this study aims at providing insights into how scholars/practitioners can identify and adopt the best-fitting approaches to overcome the potential challenges of bio-hub implementation. We investigate the existing literature comprehensively to categorize the previous studies considering several aspects including the characteristics of the problem, sustainability pillars, and methodology. A holistic understanding of these aspects can offer valuable insights into BSC management while incorporating bio-hubs. This knowledge is critical in optimizing processes, enhancing efficiency, and identifying areas for improvement. Moreover, by scrutinizing the challenges faced by bio-hubs, researchers and practitioners can develop targeted strategies and solutions to mitigate potential bottlenecks, ensuring the resilience and sustainability of BSCs. This literature review bridges the existing gaps by focusing exclusively on integrating bio-hubs within BSCs, shedding light on comprehensive considerations demanded by this relatively new paradigm. Furthermore, this research seeks to not only consolidate existing studies but also identify trends and emerging perspectives, which can help make informed decisions. Therefore, the findings can be valuable for scholars, policymakers, and industry stakeholders seeking guidance in navigating the complexities of implementing bio-hubs in BSCs. To this end, a five-step guideline of Denyer and Tranfield (2009) is followed to implement a systematic literature review (SLR) within the last ten years.

The remaining contents of this review are as follows. Section 2 provides an explanation of the bio-hub concept and its economic, environmental, and social advantages. Then, the implementation challenges are discussed. In Section 3, the research methodology, research questions, and the selection criteria of the articles are explained. The results and conclusions of the in-depth analysis are presented in Section 4. Section 5 discusses future research opportunities, followed by Section 6, which summarizes the results.

2. Background

2.1. The bio-hub concept

A significant part of the bioenergy industry relies on traditional BSCs involving direct transportation from harvest sites to other facilities (e.g., a mill). This system involves the procurement of biomass feedstock through contractual arrangements with local growers (Lamers et al., 2015b). Subsequently, these feedstock are harvested, stored within proximity, and transported in bales or low-density bulk forms to the conversion facilities (Eranki and Dale, 2011). However, the conventional approach poses significant logistical and handling challenges, mainly feedstock with high moisture content (e.g., forest-based biomass). Using such a feedstock can result in the reduction of the effective payload of trucks and consequently decrease the economic and environmental sustainability of BSCs (Strandgard et al., 2021). Furthermore, storing high moisture feedstock for a long time may pose a substantial risk of biomass losses and decrease the heating value, resulting in economic significance (Routa et al., 2018). This leads to quality and quantity reduction and contributes to the undesired proliferation of fungal spores within biomass piles (Barontini et al., 2014). Also, in extreme self-ignition cases, the stored feedstock might be completely destroyed (Li et al., 2006). Finally, when stored in open yards, biomass is exposed to uncontrollable factors such as rain, ice, and wind (Toscano et al., 2022).

Recently, numerous studies have focused on tackling these challenges, proposing a new SC concept under various terms (e.g., hub, depot, and terminal). While these terms may vary across different research endeavors, their core functions remain consistent and can collectively be referred to as "bio-hub." This concept draws inspiration from the idea of advanced uniform feedstock design systems (Hess et al., 2009). The advanced system introduces strategies to create a product with higher density and efficiency while mitigating degradation rates. These tactics could range from simple mechanical actions such as crushing, chipping, shredding and grinding, bundling and baling, screening/sieving/sorting and mixing or more intricate processes like ensiling, storing, drying, pelletization, torrefaction, and pyrolysis (Gold and Seuring, 2011). Such strategies could be implemented in bio-hubs to change the physical characteristics of feedstock, such as bulk densities and moisture content, depending on the input by-product and desired output (Keith and Castillo-Villar, 2023). These processes transform biomass into a standardized format, enabling it to be treated as a commodity that can be traded in the market (Bui et al., 2023). By standardizing the material format, biomass becomes more readily available to biorefineries, facilitating continuous and consistent supply to large-scale facilities in an economically viable manner (Hess et al., 2009). Indeed, these commodities serve as intermediary products that have uniform physical and chemical attributes, improving flowability, transportability (i.e., reduced bulk density), and storability (i.e., reduced moisture content and particle size) of feedstock (Keith and Castillo-Villar, 2023). This consistency enables the use of a similar supply system infrastructure for all biomass resources, making it compatible with existing high-capacity handling and transportation systems and equipment (Lamers et al., 2015a). It is worth mentioning that challenges related to variable properties of bulk solids during feeding and handling can result in a reduction in plant throughputs of up to 50%, thus significantly impacting biorefinery efficiency (Lamers et al., 2015b). Fig. 2 demonstrates an example of bioproduction pathways for forest biomass processing in bio-hubs.

According to Lamers et al. (2015a), depot (i.e., bio-hub) facilities can be categorized into two types: standard and quality facilities. The standard facility focuses on pelletizing cellulosic feedstock (e.g., wood and agricultural residues) to enhance its quality for transportation and storage. On the other hand, the quality depot not only pelletizes but also pre-treats the feedstock for specific downstream utilizations, such as biorefinery or animal feed (Kim et al., 2018). While the depot-based decentralized approach incurs additional costs for pre-treatment and pelletization, the improved shipping logistics and bulk density lead to significant economies of scale, ultimately offsetting these extra costs and reducing transport expenses compared to the centralized system (Kim and Dale, 2016).

2.2. Economic, environmental, and social aspects of bio-hub implementation

Bundling of supply quantities and creating distribution hubs/terminals have been proposed and practiced in managing SCs in manufacturing, agriculture, and service sectors. In the case of biomass, however, there is still a need to further implement such hubs across the globe, particularly in jurisdictions with vast geography and those with a considerable number of remote communities (Mafakheri et al., 2021; Vazifeh et al., 2021). Their strategic placement, efficiency, and integration with various bioenergy sources can significantly impact the sustainability and economic viability of bioenergy production (Lautala et al., 2015).

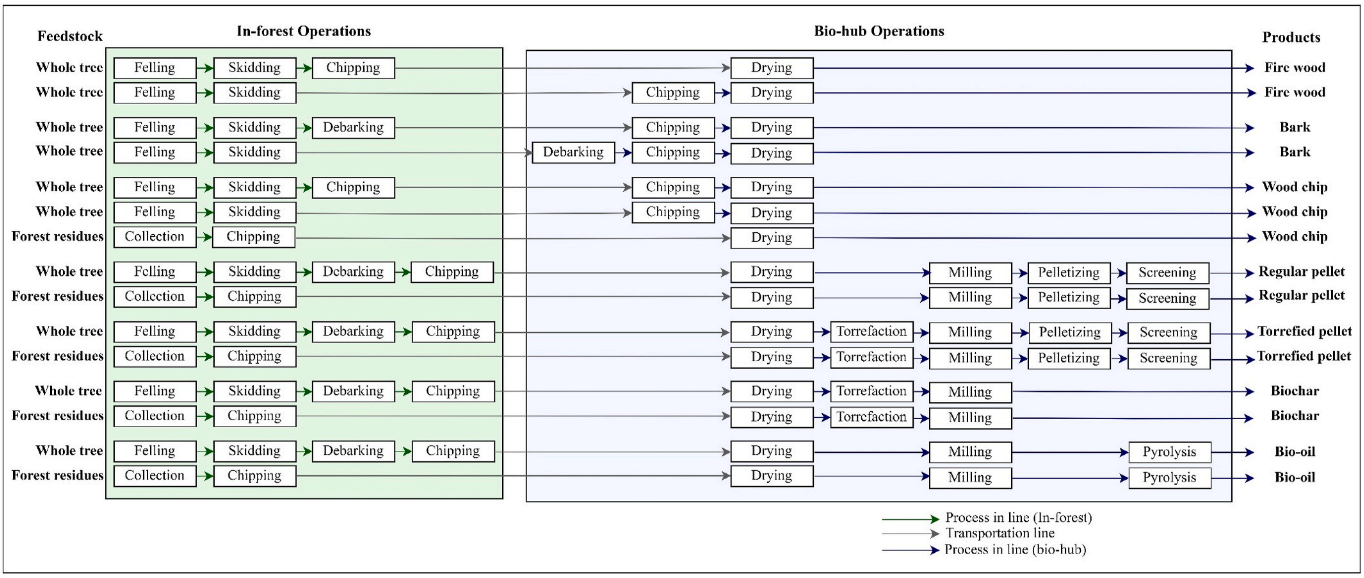

Fig. 2. A schematic of bioproduction pathways for forest biomass in a bio-hub (adopted from Pradhan et al., 2022).

According to International Energy Agency (IEA), bio-hubs can mitigate large amounts of financial risks related to feedstock supply and address challenges associated with quality, quantity, and consistency of supply. This, in turn, can facilitate access to capital budgeting, expedite project financing, and enhance policy effectiveness in bioenergy production (Nasso et al., 2020). Also, implementing bio-hubs can have indirect cost benefits by increasing supply security, economies of scale, and price stability (Virkkunen et al., 2016; Aboytes-Ojeda et al., 2022b).

From the environmental perspective, bio-hubs can reduce greenhouse gas (GHG) emissions associated with transportation through logistics optimization and biomass resource consolidation (Muerza et al., 2023). Indeed, strategically placing bio-hubs not only minimizes environmental impact but also helps reduce wildfire risk by managing biomass resources in supply areas like forests (Nicholls et al., 2022). Additionally, centralizing preprocessing activities at bio-hubs enables more efficient waste management and promotes sustainable practices. The establishment of bio-hubs in the BSC also brings notable social benefits. These include creating employment opportunities within local communities and fostering economic growth and stability. Moreover, bio-hubs can contribute to community engagement and collaboration, encouraging partnerships among various stakeholders, such as local businesses and cooperatives (Kulišić et al., 2019). Last but not least, these hubs can act as consolidated and reliable feedstock suppliers, offering contractual advantages for actors in a BSC (IEA, 2021).

2.3. *Challenges associated with bio-hub implementation*

As discussed, the successful implementation of bio-hubs in BSCs presents a promising avenue for optimizing bioenergy production; however, it comes with its own challenges requiring careful consideration. These challenges range from economic uncertainties surrounding initial investments to intricate social and policy frameworks. Below are some of the main problems associated with establishing bio-hubs.

1. *High Initial Investment and Operating Costs:* Establishing bio-hubs involves considerable costs, including infrastructure development and technology adoption, which may pose financial challenges. In addition, the operational costs of a bio-hub can significantly impact its economic feasibility, affecting its profitability and long-term viability. Each operational step in the bio-hub incurs specific expenses, contributing to the total cost of processing biomass feedstock. Such operating costs include a wide range of factors, such as energy consumption, maintenance of machinery, labor costs, and logistical considerations. Efficient management of these cost factors, which are as important as the initial investment, is crucial for optimizing the economic viability of a bio-hub (Muth et al., 2014; Gautam et al., 2022).
2. *Location Selection:* Identifying a suitable location for bio-hubs is complicated. It should be strategically situated to minimize overall cost, be accessible for feedstock suppliers, end users, and logistical infrastructure (e.g., rail ramps, in-land ports, and sea ports), and address environmental and social considerations (Berg and Athanassiadis, 2020a; Toba et al., 2023).
3. *Land Availability:* Securing suitable and adequate land for facility establishment such as bio-hubs can be challenging, especially in areas with high land demand for agricultural and/or residential purposes (Miguéis et al., 2022; Roy and Tu, 2022).
4. *Ownership:* The organizational structure and ownership of a bio-hub can affect business strategies. Bio-hubs might be controlled by other actors within BSCs (e.g., biorefineries). As such, cooperative models could be adopted to integrate bio-hubs with upstream and/or downstream actors of BSCs. Furthermore, bio-hubs can operate as standalone markets. These hubs are expected to function autonomously in this scenario, operating as financially independent and efficient business entities (Lamers et al., 2015b; Mafakheri et al., 2021; Nicholls et al., 2022).
5. *Biomass Availability:* The size and technical layout of a bio-hub will be influenced by the availability and seasonality of feedstock (Castillo-Villar et al., 2017). In addition, a flexible and reliable biomass supply is necessary for bio-hubs to operate all year. Furthermore, seasonality and weather conditions can lead to variations in availability and potential disruptions in feedstock supply (Lamers et al., 2015b; Soren and Shastri, 2019).

3. Review methodology

To assess the current research landscape and consolidate scholarly efforts regarding the implementation of bio-hubs, an SLR within this domain is conducted. An SLR is a rigorous and structured approach to analyzing existing research in a particular field. It involves the predefined process of searching, evaluating, and synthesizing relevant studies to answer specific research questions or address particular objectives. Hence, an SLR helps researchers comprehensively survey the available body of knowledge on a particular topic, providing a solid foundation for building new research or making informed decisions. It ensures transparency and reproducibility in the review process by clearly documenting the search strategy and inclusion/exclusion criteria, enhancing its credibility (Han et al., 2020). Accordingly, this study follows the five-step guideline of Denyer and Tranfield (2009) to implement the SLR. This methodology has also been adopted by other literature review studies, such as Ali et al. (2017), Han et al. (2020), and Llaguno et al. (2022). These steps are as follows (Denyer and Tranfield, 2009).

I) **Formulating the research question(s)**: The first critical step in conducting an SLR is meticulously defining the study's scope. This includes establishing the boundaries of the research and pinpointing the specific research questions that will provide direction throughout the review process. As such, researchers lay a solid foundation for a well-structured and purposeful SLR. Regarding the explanations given in the previous section, the primary goal of this study is to assess the impact of integrating bio-hubs in BSCs by addressing the following research questions:

> **Q1**: What key levels of analysis and decision-making are addressed in the literature?
>
> **Q2**: What methodologies and metrics have been employed in assessing bio-hub implementations, and how do these methodologies influence research outcomes?
>
> **Q3**: What recommendations can be drawn from the literature to enhance the successful integration of bio-hubs within the BSC?

II) **Searching and identifying core studies**:There are arguably two major abstract and citation databases, i.e., Web of Science (WOS) and Scopus, that collectively cover nearly 95% of all research publications, providing a comprehensive information base (Spieske and Birkel, 2021). To maintain impartiality and comprehensiveness, these two databases were utilized to retrieve articles published in internationally peer-reviewed journals. All studies published within the ten-year period preceding the end of March 2024 are covered. To identify and list core papers related to the review questions, as per the second step of the adopted guideline, it is necessary to establish an initial set of keywords. To have a comprehensive list of keywords, first, a number of highly cited papers were selected based on the current list. By analyzing these influential papers, researchers can identify common themes, concepts, or terminologies frequently used in the field, contributing to the comprehensiveness of the keyword list. Then, their keywords and derivatives were added to the initial list of keywords to find relevant articles. These steps were repeated to expand the keyword list until it reached a stage encompassing all commonly used keywords. It is worth mentioning that the query was used to explore the database with a focus on the titles, abstracts, and/or keywords of the publications. The final list of keywords is as follows, where similar terms are grouped within the same category using the Boolean operator "OR" and the Boolean operator "AND" combines these three categories.

(hub OR terminal OR depot OR yard OR "distribution facility" OR "storage facility" OR "distribution center(re)" OR "storage centre(re)" OR "preprocessing facility" OR "pre-processing facility" OR "pretreatment facility" OR "pre-treatment facility" OR "logistics center(re)" OR "collection centre(re)" OR "collection facility") AND (biomass OR bio-mass OR bioenergy OR bio-energy OR biofuel OR bio-fuel OR bioethanol OR bio-ethanol OR biogas OR bio-gas OR biodiesel OR bio-diesel OR "bio oil" OR bio-oil OR biorefinery OR bio-refinery) AND ("supply chain" OR "supply-chain" OR logistics)

III) **Selecting the related papers**: After initial screening of the articles using the defined search query and the criteria established in the previous stages, a thorough evaluation is essential. In total, 158 and 144 records were found in WOS and Scopus, respectively. It is noteworthy that the removal of keywords related to bio-hubs (e.g., hub, terminal, depot, distribution center, storage center, and yard) would result in publication counts of 2955 and 3581, respectively. This substantial difference underscores that a relatively small portion of the papers addressing BSCs have explicitly integrated the concept of bio-hubs. Then, the duplicates were identified and removed. Afterwards, the titles and abstracts of the remaining articles underwent a screening based on the exclusion and inclusion criteria. This step excludes studies that do not meet the predetermined criteria. The peer-reviewed journal papers (i.e., published, in-press, and pre-publication versions) written in English about bio-hub implementation problems in BSCs were shortlisted. As such, conference papers are excluded from this study (Habibi et al., 2023). Also, the aim was to identify the articles that specifically state their research objectives as quantitative investigation or assessment of the BSC decisions, effects, benefits, or challenges associated with bio-hub implementation in BSCs. These criteria have been listed in Table 1. By examining the abstracts, the selected articles for additional full-text review were identified.

The full texts of the articles were then evaluated to ensure the quality and relevance of the remaining papers. Moreover, the reference lists of the short-listed papers were thoroughly scrutinized based on the inclusion and exclusion criteria. As a result, 212 papers were eliminated due to duplication, insufficient connection to the topics, and lack of transparency in concepts and ideas. Finally, this comprehensive examination resulted in 90 journal articles to conduct more in-depth analyses. These steps include analysis and synthesis of findings, as well as the presentation of results presented in the following sections. Fig. 3 illustrates the summary of the steps taken to identify the shortlisted papers.

4. Research findings

In this section, descriptive and quantitative analyses are conducted to have a deep understanding of the shortlisted papers. These publications are investigated in terms of their journals and geographical distribution in the descriptive analysis subsection. Then, they are categorized and examined in-depth from modeling and input-output perspectives.

As discussed in the preceding sections, several terms have been used to refer to the bio-hub concept. Findings indicate that "depot", "terminal", and "hub" are more commonly adopted than the other ones. Based on the descriptions provided in these studies, it seems that "terminal" is predominantly utilized when authors intend to refer to a logistical node where biomass is stored, loaded, and often chipped for subsequent transportation activities. However, alternative terms are frequently employed when implementing more complex processes, such as drying and pelletization. It should be noted that these terms are used interchangeably throughout this study. Table 2 Illustrates the frequencies of the bio-hub terms.

Table 1
Review exclusion and inclusion criteria adapted from Ghobakhloo (2020) and Iftikhar et al. (2024).

Category	Criteria	Description
Exclusion	A	Any article not characterized as a peer review article (e.g., conference papers, book chapters, notes, books, and thesis/dissertations)
	B	Any article without full text
	C	An article not written in English;
	D	Any article that did not implement a quantitative investigation or assessment associated with bio-hub implementation in a BSC
Inclusion	A	Any article which is peer-reviewed and formally accepted for publication
	B	Bio-hub implementation in the context of a BSC must be the core focus of the article
	C	A quantitative methodology was used for modelling and analysis

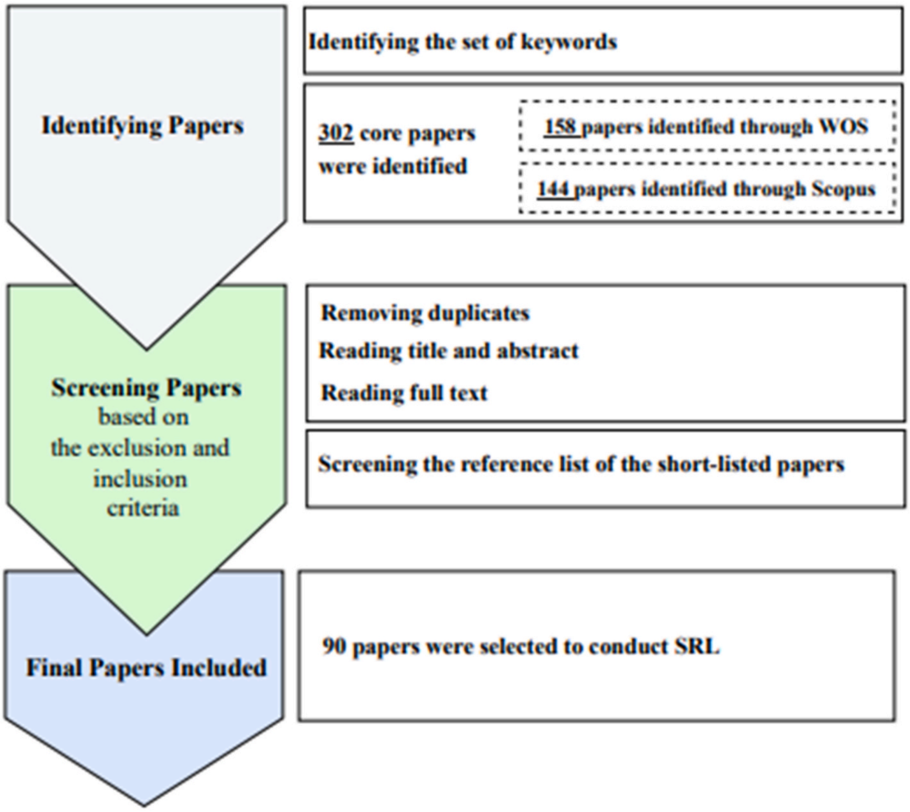

Fig. 3. Review process of finding suitable papers in the SLR.

Table 2
The frequency of bio-hub terms.

Bio-hub Term	Frequency	Bio-hub Term	Frequency
Depot	36	Terminal	18
Hub	16	Collection center	5
Storage facility	3	Yard	2
Preprocessing facility/center	2	Pre-treatment center	2
Integrated biomass logistics centre (IBLC)	2	Mobile pyrolysis system	1
Regional biomass collection depot	1	Distribution facility	1
Regional biomass preprocessing depot (RBPD)			1

4.1. Descriptive analysis

The number of papers published in each journal is displayed in Table 3. The range of these journals is wide and includes 42 journals. Notably, the journals "*Applied Energy*", "*Journal of Cleaner Production*", "*Biomass and Bioenergy*", "*Energies*", "*Biofuels, Bioproducts and Biorefining*", "*Bioresource Technology*", and "*GCB Bioenergy*" hold the largest share and contributed nearly 50% of the publications. Also, the geographical distribution of papers worldwide was extracted based on the authors' affiliation, shown in Fig. 4. The degree of color in the visualization denotes each country's contribution level. A total of 25 countries were included in the literature, with the United States of America (USA) and Canada emerging as the leading contributors.

4.2. Quantitative analysis of bio-hub implementation

To address challenges associated with bio-hub implementation in BSCs, some researchers have focused on real-world studies and case examples. This section examines the main features of the selected papers (e.g., objectives and decision variables), along with their findings. To streamline studies focusing on similar aspects of incorporating bio-hubs, papers are categorized based on their modeling approaches, including mathematical programming, simulation, multi-criteria decision-making (MCDM), and systematic modeling. Indeed, each set of modeling methodologies proves effective in addressing specific facets of bio-hub integration. Within each category, the specific focus of each study and its significance are discussed in the following sections.

4.2.1. Mathematical programming

A prevalent trend in the literature reveals the widespread application of mathematical programming, constituting 70% of the papers published (i.e., 64 out of 90). This category includes mixed-integer programming, linear programming, non-linear programming, stochastic programming, fuzzy programming, and P-graph modeling. These studies examine strategic (long-term), tactical (mid-term), and operational (short-term) decisions, which collectively contribute to the understanding of how hub implementation impacts BSC performance. A comprehensive summary of these studies has been provided in Table 4.

According to this table, scholars have primarily focused on strategic decisions at the upstream level, mainly determining the optimal location and number of bio-hubs, along with their allocation to diverse resources and markets. Establishing a bio-hub requires a significant investment of time and financial resources, making it challenging to alter decisions once made (Gautam et al., 2022). As such, evaluating the economic feasibility of these facilities during the planning phases is of cardinal importance (Martinkus et al., 2018). This issue is clearly evident from Table 4 since the primary objective across all these studies was optimizing economic factors. These factors include minimizing the total cost of bio-hubs (e.g., capital cost, logistics, purchasing, and inventory costs) along with other BSC costs or maximizing the net present value and profit of these hubs. Alongside the economic aspect, minimizing the environmental footprint related to bio-hub implementation, particularly

Table 3
Distribution of journals and published papers.

Journal	No. of Papers	Journal	No. of Papers
Applied Energy	10	Journal of Cleaner Production	7
Biomass and Bioenergy	7	Energies	5
Bioresource Technology	4	Biofuels, Bioproducts and Biorefining	4
GCB Bioenergy	4	Computers & Industrial Engineering	3
Transportation Research Part E: Logistics and Transportation Review	3	Annals of Operations Research	3
Renewable Energy	3	IISE Transactions	3
Sustainability	2	Forests	2
ACS Sustainable Chemistry & Engineering	2	Scandinavian Journal of Forest Research	2
International Journal of Production Research	1	Renewable and Sustainable Energy Reviews	1
Applied Mathematical Modelling	1	Energy	1
Chemical Engineering Transactions	1	Energy Technology	1
Clean Technologies and Environmental Policy	1	IEEE Transactions on Evolutionary Computation	1
Computers & Chemical Engineering	1	Frontiers in energy research	1
The International Journal of Life Cycle Assessment	1	Environmental Management	1
International journal of energy research	1	Annals of Forest Research	1
Mathematics	1	Sensors	1
International Journal of Forest Engineering	1	Canadian Journal of Forest Research	1
International Journal of Chemical Reactor Engineering	1	Environmental Science and Pollution Research	1
Biosystems Engineering	1	Renewable Energy Focus	1
Sustainable Energy Technologies and Assessments	1	BioEnergy Research	1
Transportation Research Record	1	Sustainable Production and Consumption	1

GHG emissions, has been proposed in 11 out of 64 cases. Moreover, maximizing the social objective of job creation was another objective function recognized in 3 out of the 64 cases examined. These factors collectively highlight the importance of sustainable bio-hub planning.

One of the main functions of bio-hubs is to consolidate shipments and consequently reduce the number of direct routes between origin and destination points. Accordingly, improving economies of scale can lead to a decrease in transportation costs (Aranguren et al., 2021). To facilitate the integration of hubs into BSCs, hub-and-spoke models have been proposed (Roni et al., 2014, 2017; Aranguren et al., 2018, 2021; Aranguren and Castillo-Villar, 2022; Aboytes-Ojeda et al., 2022b). The hub-and-spoke networks can be helpful in designing large-scale BSCs while minimizing the total cost of the system (Roni et al., 2014). As illustrated in Aboytes-Ojeda et al. (2022b), bio-hubs can reduce transportation costs by efficiently delivering densified biomass over long distances and in large quantities using high-capacity transport vehicles.

In addition to bio-hub location and biomass flow planning (i.e., amount of feedstock transshipped to/from bio-hubs), capacity planning is another important aspect that warrants examination during the BSC design process. Such decisions directly impact the efficiency and resilience of BSCs and responsiveness to supply and demand fluctuations (Salehi et al., 2022; Esmaeili et al., 2023). This issue has been addressed in about 30% of the studies in this category (See Fig. 5). Some scholars have leveraged the benefits of bio-hub implementation by optimizing vehicle routing, resource management, technology selection, and production planning of bio-hubs.

Given the inherent uncertainty and disruptions within all SCs, particularly BSCs, ignoring their effects and proposing deterministic models can lead to infeasible or sub-optimal solutions (Habibi et al., 2023). Results indicate that 30% of papers within this category have considered uncertainty factors such as feedstock quality (e.g., moisture content), feedstock quantity, market demand fluctuation, price, and transportation-related factors (e.g., loading, unloading, and transportation time) in their bio-hub planning problems. In these papers, two-stage stochastic optimization has been mostly used to model problems. In addition to these operational risks (i.e., high frequency and low impact), some researchers highlighted the necessity of planning for disruption risks (particularly for low frequency but high impact disruptions) during the design stage, particularly when implementing capital-intensive facilities such as bio-hubs. Liu et al. (2017) demonstrated the effect of disruption risks on optimal bio-hub locations and supply chain costs. According to Marufuzzaman et al. (2014), when site-dependent probabilistic disruptions (e.g., flooding, hurricanes, and drought) are considered in the planning phase, the model locates hubs in areas with low disruption probabilities. Maheshwari et al. (2017) concluded that incorporating resiliency in design phase led to a reduction of up to 38% in the expected disruption cost of the BSC by optimizing depot locations (Maheshwari et al., 2017). Similarly, Soren and Shastri (2019) demonstrated that considering disruption (i.e., supply disruption in the form of drought) at the design stage can reduce the expected SC costs. They claimed this cost saving can be increased even by increasing the disruption intensity. In this study, the saving amount was proposed as a penalty function on additional feedstock and shortfall. Fig. 6 presents the frequency of risk factors.

Therefore, incorporating such factors enables decision-makers to design a resilient bio-hub integrated network that operates efficiently in the face of disruptions. Although these results depend on the level and nature of disruptions and other parameters, the important finding is that presenting depots can increase BSC resilience if planned and designed meticulously.

Findings illustrate that some studies developed integrated approaches to enhance the capabilities of the applied mathematical modeling in finding optimal decisions using agricultural land management with numerical assessment criteria (ALMANAC) simulation, geographic information system (GIS), machine learning (ML), and MCDM. For example, ALMANAC simulation was employed to predict plant yield in different locations under climate changes (Aranguren et al., 2018). GIS, which can analyze geographical information, was used to determine feedstock supply and facility locations at high spatial resolution (He-Lambert et al., 2018; Ng et al., 2018). Goettsch et al. (2020) applied multiple ML methods in their study to decrease the number of potential depot locations given to the mathematical model and increase the quality of the solution. Furthermore, Gautam et al. (2022) implemented the analytic hierarchy process (AHP) along with mathematical programming separately to determine the location of terminals based on qualitative and quantitative criteria, respectively. Then, the authors employed benefit-cost analysis to incorporate the results of these two approaches. Data envelopment analysis also was used to assess the efficiency of potential alternatives and inject the selected ones into the mathematical programming model to choose the final locations (Babazadeh et al., 2017).

Regarding the solution method, solvers (e.g., CPLEX and Gurobi) have been mostly used to solve the mathematical models. When dealing with problems including non-linear terms, multiple decision variables, especially binary ones, and stochastic parameters, solving models using these solvers can pose significant challenges (Tiwari et al., 2021). To solve such complex and large-scale problems, different methods like decomposition-based algorithms (e.g., multicut L-shaped decomposition, branch and bound, and benders) and heuristic/metaheuristic algorithms (e.g., genetic algorithm, simulated annealing, ant colony, and tabu search) have been used to provide the solutions to mathematical

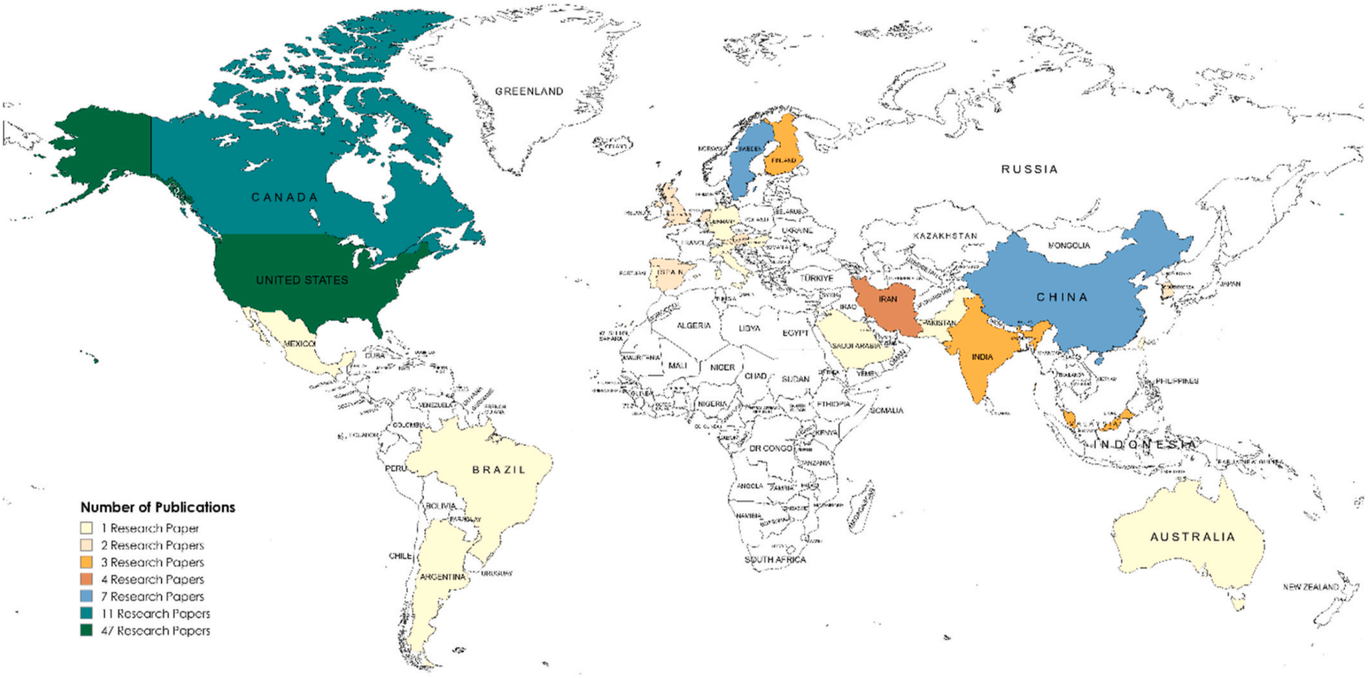

Fig. 4. The spatial spread of participating countries.

programs.

4.2.2. Simulation

BSCs are subject to be influenced by multiple factors ranging from the seasonality of biomass availability to the intricacies of transportation logistics and storage (Mafakheri et al., 2021). Simulation is a powerful approach to analyzing such a complex and dynamic environment, enabling quantitative assessment of system behavior. This approach provides a flexible environment to model any relationship among actors and multiple variabilities, allowing for the incorporation of a high degree of complexity (Habibi et al., 2023). Simulation is commonly employed to explore "what if" scenarios, offering valuable insights into a system's performance over time (Katsaliaki et al., 2021). Indeed, this approach enables researchers to meticulously analyze network activities, facilitating efficient decision-making at both tactical and operational levels. Therefore, stakeholders can make informed decisions regarding various aspects of bio-hubs before initiating any investments. Findings show that this category comprises almost 10% of shortlisted papers, with a focus on resource utilization and biomass flow planning under certain bio-hub scenarios (see Table 5). Moreover, the main sustainability aspect investigated in this category was the economic viability of the proposed bio-hub scenarios. These studies are further discussed as follows.

Using discrete event simulation (DES), Wolfsmayr et al. (2016) simulated the terminal processes to investigate the efficiency of adopting existing railway sidings to provide multimodal terminals for primary forest fuel transportation. They analyzed the daily and annual transshipment capacities and figured out bottlenecks in different terminal layouts under supply scenarios. Moreover, Väätäinen et al. (2017) examined the performance of a BSC with intermediate terminals at different distances. To this end, terminal-related factors such as location, investment cost, transport method, truck utilization, and quality of terminal-stored feedstock were investigated. In a similar work, Fernandez-Lacruz et al. (2019) investigated the usefulness of terminals in supplying biomass to a combined heat and power plant (CHP) and biorefineries with varying sizes. They calculated the cost of feedstock handling in two scenarios, direct or combined via terminal transportation. Parameters such as machine efficiency, material flow, demand loss, and dry matter losses during storage were measured to compare these two scenarios. Using DES, Enström et al. (2021) studied the cost-efficiency of delivering feedstock to the port using intermediate terminals. The main aim of this study was to streamline logistics operations at the loading port for maritime transport of woody biomass. All these studies revealed that establishing such a terminal allows for buffer inventory to manage uncertainty and facilitates the transportation of a high volume of biomass to other facilities (e.g., bioenergy plants).

The second simulation technique used in bio-hub implementation literature is system dynamics. This technique utilizes mathematical equations to represent the interactions and feedback loops within a system, providing insights into how changes in one part can affect the entire system (Nasiri et al., 2016). Using system dynamics modeling, Khoddami et al. (2021) explored two distinct coordination strategies, namely quantity discounts and cost-sharing in a hub-coordinated SC, to derive the optimal decisions for each actor of a BSC.

4.2.3. Multi-criteria decision-making (MCDM)

MCDM methods are analytical approaches used when making choices involving multiple, often conflicting criteria. These methods assist in evaluating and comparing various alternatives by considering diverse qualitative and quantitative factors simultaneously. MCDM involves assessing options against a set of predefined criteria, assigning weights to these criteria based on their importance, and ultimately ranking or selecting the most suitable alternative. The goal is to provide a systematic and structured framework for decision-makers to navigate complex decision landscapes, ensuring a more informed decision-making process (Mottaghi et al., 2022). There are several MCDM techniques, such as the technique for order preference by similarity to ideal solutions (TOPSIS), decision-making trial and evaluation laboratory (DEMATEL), elimination and choice translating reality (ELECTRE), analytic network process, and AHP, which are different in terms of their characteristics (Kumar et al., 2017). However, within the literature of this category summarized in Table 5, content analysis reveals the utilization of AHP and TOPSIS. Given the advantages of MCDM techniques in simultaneously analyzing different criteria and alternatives, location selection of bio-hubs has been mostly studied in these papers. Below, we further discuss these papers.

Table 4
Summary of mathematical programming applications in bio-hub implementation problems.

Authors (year)	Bio-Hub Term	Problem	Sustainability Pillar	Modeling Approach	Solution Method	Uncertainty factor	Case Study	Feedstock Type	Final Bioproduct Type
Zhang et al. (2014)	Hub	Lo & BF	Eco	Mathematical programming	Solver		USA	Woody biomass	Commodity chemicals
Marufuzzaman et al. (2014)	Hub	Lo & BF	Eco	Mathematical programming	Accelerated benders decomposition algorithm	Site dependent disruptions	USA		Bioethanol
Xie et al. (2014)	Hub	Lo & BF	Eco	Mathematical programming	Solver		USA	Corn stover & forest residues	Bioethanol
Akhtari et al. (2014)	Terminal	BF & IP	Eco	Mathematical programming	Solver		Canada	Logging residues & sawmill wastes	Heat
Roni et al. (2014)	Depot	Lo & BF	Eco	Mathematical programming	Benders decomposition algorithm		USA	Cellulosic biomass	Biofuel
Lautala et al. (2015)	Depot	Lo	Eco	Mathematical programming (Software-based)	Solver		USA	Woody biomass	Biofuel
Poudel et al. (2016)	Depot	Lo & BF	Eco	Mathematical programming $ spatial statistics model	Benders decomposition algorithm	Failure probability associated with link	USA	Corn stover & forest residues	Biofuel
Marufuzzaman et al. (2016)	Terminal	Lo, CP & BF	Eco	Mathematical programming	Solver		USA	Forest residues	Syngas
How et al. (2016)	Hub	Lo & BF	Eco	Mathematical programming & P-graph	Decomposition algorithm		Malaysia	Agricultural residues	
Zhang et al. (2016)	Yard	Lo, CP & BF	Eco	Mathematical programming	Solver		USA	Woody biomass	Bioethanol
Chugh et al. (2016)	Hub	Lo, PP & BF	Eco	Mathematical programming	Solver		USA	Switchgrass	Bioenergy
Lin et al. (2016)	Hub	Lo & BF	Eco	Mathematical programming	Solver		USA	Agricultural residues	Bioethanol
Li et al. (2017)	Pre-treatment facility	Lo & BF	Eco	Mathematical programming &	Solver		USA	Woody biomass	Biofuel
Ng and Maravelias (2017a)	Depot	Lo, CP, TS & BF	Eco	Mathematical programming	Solver		USA	Agricultural residues	Bioethanol
Maheshwari et al. (2017)	Depot	Lo, CP & BF	Eco	Mathematical programming	Solver based on scenarios	Supply disruption	USA	Corn stover, switchgrass, & miscanthus	
Ng and Maravelias (2017b)	Depot	Lo	Eco	Mathematical programming	Solver		USA	Agricultural residues	Bioethanol
Babazadeh et al. (2017)	Pre-treatment center	Lo & BF	Eco	Mathematical programming & data envelopment analysis	Solver		Iran	Jatropha curcas L. & waste cooking oil	Biodiesel
Zamar et al. (2017)	Depot	BF & VRP	Eco	Mathematical programming	Quantile-based scenario analysis	Feedstock quality, loading, unloading, & transportation time	Canada	Sawmill residues	
Roni et al. (2017)	Depot	Lo & BF	Eco, Env, & Soc	Mathematical programming	Augmented ϵ-constraint		USA	Cellulosic biomass	Bioethanol
Méndez-Vázquez et al. (2017)	Hub	Lo & BF	Eco & Env	Mathematical programming	Solver		Mexico	Agricultural residues	Solid biofuel (pellet)
Gautam et al. (2017)	Terminal	Lo & BF	Eco	Mathematical programming	Solver		Canada	Woody biomass	
Quddus et al. (2017)	Depot	Lo, CP & BF	Eco & Env	Two-stage stochastic modeling	Sample average approximation & progressive hedging algorithm	Supply	USA	Pellet	
Abasian et al. (2017)	Terminal	Lo & BF	Eco	Mathematical programming	Solver		Canada	Woody biomass	
Liu et al. (2017)	Collection center	Lo & BF	Eco	Mathematical programming	Solver	Disruption in collection center &	China	Wheat straw	Biofuel

(continued on next page)

Table 4 (*continued*)

Authors (year)	Bio-Hub Term	Problem	Sustainability Pillar	Modeling Approach	Solution Method	Uncertainty factor	Case Study	Feedstock Type	Final Bioproduct Type
						feedstock seasonality			
Shamsi et al. (2018)	Collection center	Lo, CP & BF	Eco	Mathematical programming	Solver		Iran	Wheat straw	Bioethanol
Ng et al. (2018)	Depot	Lo, CP & BF	Eco	Mathematical Programming & GIS	Solver		USA	Corn stover	Bioethanol
Malladi et al. (2018)	Yard	BF & VRP	Eco	Mathematical programming	Decomposition-based approach		Canada	Woody biomass	
Dafnomilis et al. (2018)	Terminal	RM	Eco	Mathematical programming	Solver		Netherlands	Wood pellet	
Sarker et al. (2018)	Hub	Lo & BF	Eco	Mathematical programming	Branch & bound			Crops, grass & wood residue, & livestock waste	Biomethane gas
He-Lambert et al. (2018)	Preprocessing center	Lo & BF	Eco	Mathematical programming & GIS	Solver		USA	Switchgrass	Biofuel
Aranguren et al. (2018)	Depot	Lo & BF	Eco	Mathematical programming & ALMANAC simulation	Solver		USA	Switchgrass	Biomass co-firing
Asadi et al. (2018)	Distribution facility	Lo, BF & VRP	Eco & Env	Mathematical programming	Genetic algorithm & multi-objective particle swarm optimization	Demand	Iran	Algae	Biofuel
Roni et al. (2019)	Depot	Lo, CP & BF	Eco	Mathematical programming	Solver	Feedstock quality	USA	Agricultural residue, energy crops & municipal solid waste	Bioethanol
Sarker et al. (2019)	Hub	Lo, BF & VRP	Eco	Mathematical programming	Genetic algorithm			Crops, grass & wood residue, & livestock waste	Biomethane gas
Abasian et al. (2019)	Terminal	Lo & BF	Eco	Two-stage stochastic modeling	Multicut L-shaped decomposition algorithm	Demand & final product price	Canada	Woody biomass	
Soren and Shastri (2019)	RBPD	Lo, CP & BF	Eco	Mathematical programming	Solver based on the scenario	Supply disruption		Agricultural residues	
Saadati and Hosseininezhad (2019)	Hub	Lo, CP & BF	Eco	Mathematical programming	ϵ-constraint		Iran	Bagasse	Bioethanol
Poudel et al. (2019)	Hub	Lo, CP & BF	Eco	Two-stage stochastic modeling	Nested decomposition algorithm, rolling horizon algorithm & variable fixing technique	Feedstock quantity	USA	Corn stover & woody biomass	Biofuel
Aguayo et al. (2019)	Storage facility	Lo & BF	Eco	Mathematical programming	Branch-and-price-based method		USA	Switchgrass	Bioethanol
Berg and Athanassiadis (2020a)	Terminal	Lo & BF	Eco	Mathematical programming	Solver		Sweden	Round wood & logging residues	
Aboytes-ojeda et al. (2020)	Hub	Lo & BF	Eco	Two-stage stochastic modeling	Simulated annealing & Tabu search	Feedstock quality	USA		Bioethanol
Guo et al. (2020)	IBLC	PP & RM	Eco	Mathematical programming	Solver		Spain	Wheat straw & wood chips	Fuel pellet
Goettsch et al. (2020)	Depot	Lo & BF	Eco	Two-stage stochastic modeling & ML	Solver	Feedstock quality	USA	Switchgrass	Biomass co-firing
Agar et al. (2020)	Terminal	BF	Eco	Mathematical programming	Solver		Sweden	Woody biomass	
Aranguren et al. (2021)	Depot	Lo & BF	Eco	Two-stage stochastic modeling & ALMANAC simulation	Solver	Feedstock quality	USA	Switchgrass	Biomass co-firing
Nur et al. (2021)	Depot	Lo, CP & BF	Eco	Two-stage Stochastic modeling	Sample average approximation & progressive	Feedstock quality	USA	Corn stover & switchgrass	Bioethanol

(*continued on next page*)

Table 4 (*continued*)

Authors (year)	Bio-Hub Term	Problem	Sustainability Pillar	Modeling Approach	Solution Method	Uncertainty factor	Case Study	Feedstock Type	Final Bioproduct Type
					hedging algorithm				
Hossain et al. (2021)	Depot	Lo & BF	Eco	Mathematical programming	Solver		USA	Corn stover & switchgrass	Cellulosic biofuel
Mafakheri et al. (2021)	Hub	BF	Eco	Mathematical programming	Solver		Canada	Wood pellet	Electricity
Mao et al. (2021)	Storage facility	Lo & BF	Eco & Env	Mathematical programming	Genetic algorithm		China	Wheat straw	
Cao et al. (2021)	Collection center	Lo, BF & VRP	Eco	Mathematical programming	Neighbourhood search & tabu search				
Rahimi et al. (2021)	Collection center	Lo, CP & BF	Eco	Mathematical programming	Solver		Iran	Animal waste	Electricity
Aranguren and Castillo-Villar (2022)	Depot	Lo & BF	Eco & Env	Two-stage Stochastic modeling	ϵ-constraint method, particle swarm optimization & simulated annealing	Feedstock quantity	USA	Switchgrass	Biomass co-firing
Aboytes-Ojeda et al. (2022b)	Depot	Lo & BF	Eco	Two-stage Stochastic modeling	L-shaped with connectivity constraints	Feedstock quality	USA	Switchgrass	Bioethanol
Zarei et al. (2022)	Storage facility	Lo & BF	Eco	Multistage risk-based stochastic model	Solver	Feedstock quantity & demand	South Korea,	Pellets, wood chips & seaweed	Biofuel
Abusaq et al. (2022)	Depot	Lo, CP & BF	Eco & Env	Mathematical programming	Fuzzy flexible robust possibilistic programming	Feedstock quantity & demand	Pakistan	Agricultural residue	Bioenergy
Gautam et al. (2022)	Terminal	Lo & BF	Eco & Soc	Mathematical programming, MCDM & benefit-cost analysis	Solver		Canada	Woody biomass	Heat & electricity
Geismar et al. (2022)	Depot	Lo, CP & BF	Eco	Stochastic modeling	Decomposition algorithm	Feedstock quantity	USA	Lignocellulosic biomass	Bioethanol
Abbasi et al. (2022)	Collection center	Lo, BF & VRP	Eco & Env	Mathematical programming	Solver & Genetic algorithm		Iran	Municipal solid waste	Electricity
Lam et al. (2023)	Hub	Lo, BF & TS	Eco	Mathematical modeling & P-graph	Solver		Malaysia	Agricultural residues	
Li et al. (2023)	Depot	Lo, BF & VRP	Eco & Env	Mathematical programming	Genetic & ant colony algorithms				
Pandey et al. (2023)	Preprocessing facility	Lo, CP & BF	Eco & Env	Mathematical programming	Solver	Feedstock quantity	USA	Corn stover	Bioethanol
Li et al. (2024)	Depot	Lo & BF	Eco	Mathematical programming	Solver		USA	Forest residues	Biofuel
Hossain et al. (2024)	Depot	Lo, BF, CP & VRP	Eco	Mathematical programming	Solver		USA	Miscanthus, switchgrass & corn stover	Biofuel
Singh et al. (2024)	Depot	Lo, BF& CP	Eco, Env, & Soc	Mathematical programming	Augmented ϵ-constraint & lexicographic technique			Waste animal fat	Biodiesel

Eco: Economic, **Env:** Environmental, **Soc:** Social, **Lo:** Location, **BF**: Biomass Flow, **CP:** Capacity Planning, **RM:** Resource Management, **VRP:** Vehicle Routing Problem, and **PP:** Production Planning.

Kühmaier et al. (2014) defined a suitability index for potential terminal locations using AHP and fuzzy set theory. They integrated the stakeholder preferences and spatial constraints to calculate this index. Similarly, Lemire et al. (2019) applied AHP to weight location selection criteria of depots. How and Lam (2017) proposed an integrated approach using AHP and principal component analysis (PCA) to determine the location of processing hubs. In a recent study, which can be categorized in both MCDM and simulation models, Muerza et al. (2023) presented a decision support system for biomass procurement planning of IBLC. They used AHP for weighting the pre-determined criteria to be considered in the IBLC supplier selection problem and employed TOPSIS for ranking these suppliers. Then, to compare the economic and environmental feasibility of implementing IBLC with these suppliers, they integrated agent-based simulation and DES. They concluded that considering these centers increases the total profit by 55% while CO_2 equivalent emission is reduced by 24.2%.

4.2.4. Systematic modeling

Apart from the strategic and tactical/operational decisions regarding bio-hubs discussed in the prior sub-sections, this subsection examines papers that scrutinize the technical aspects of operations within bio-hubs and the resultant performance of the network. Findings indicate that 27% of the shortlisted papers fall within this category, where techno-economic analysis (TEA) and life cycle assessment (LCA)

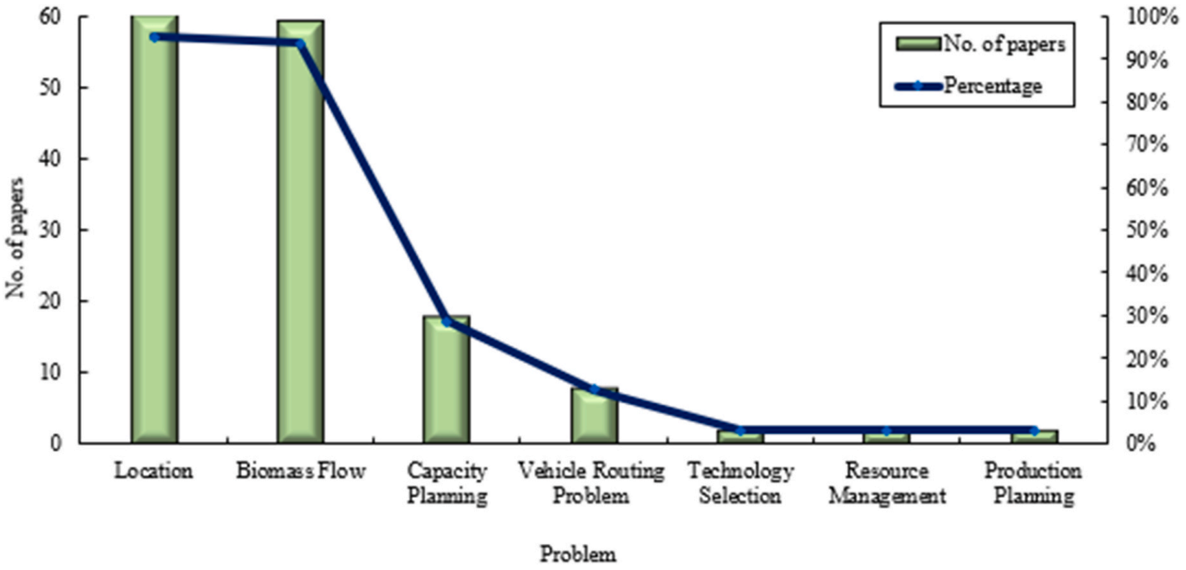

Fig. 5. The frequency of problems optimized through mathematical programming.

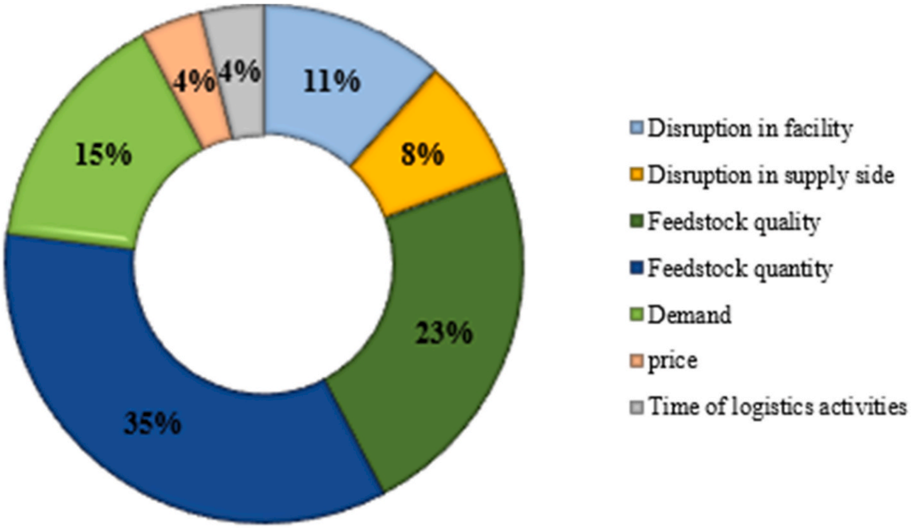

Fig. 6. Frequency of risk factors.

techniques have been predominantly employed. However, a few other analyses using financial analysis, descriptive statistics, and ML methods have been conducted as well, which have been summarized in Table 6. It should be mentioned that systematic modeling in these papers can include a variety of techniques such as TEA, LCA, financial analysis, structural analysis, regression analysis, descriptive statistics, software-based modeling, decision support system, input/output analysis, and statistical hypothesis testing (Jazinaninejad et al., 2022).

TEA is a methodological approach that assesses the economic feasibility and viability of a technological process (Lamers et al., 2015a). It involves the detailed examination of both the technical aspects and the economic factors associated with the development, implementation, and operation of a technology or process. As such, incorporating technological considerations is crucial for a comprehensive assessment of the feasibility, efficiency, and sustainability of bio-hubs in addition to addressing the economic aspects (Lan et al., 2021). To this end, TEA has been implemented in some studies to compare the bio-hub concept with traditional systems and investigate the effect of preprocessing technologies that can be implemented within bio-hubs.

Muth et al. (2014) considered two logistics concepts: a traditional bale logistics system and an advanced supply system, including preprocessing biomass depots. Comparing the efficiency of these two systems, they concluded that the economies of scale enabled by the advanced supply system compensate for a considerable portion of the added logistics costs associated with additional depot transportation and processing activities. As a result, the final product incurs a slightly higher selling price compared to the traditional logistic system. Lamers et al. (2015a) analyzed three depot configurations to assess the economic viability of considering depots with different technical activities. They considered two standard depots with different technologies (i.e., conventional pelleting process and high-moisture pelleting process) and one quality depot with ammonia fiber expansion technology.

Similar to the previous study, they claimed that the benefits associated with depot facilities could outweigh the added costs. Patel et al. (2019) modeled different BSC models and investigated the technical and financial viability of switching from centralized to decentralized pyrolysis units (i.e., bio-hub). The decentralized pyrolysis system has the capability to adjust or modify its operations and processes in response to the specific conditions and environmental factors of different geographic regions and varying weather conditions. They finally

Table 5
Summary of simulation and MCDM applications in bio-hub implementation problems.

Authors (year)	Bio-Hub Term	Problem	Sustainability Pillar	Modeling Approach	Aim	Case Study	Feedstock Type	Final Bioproduct Type
Wolfsmayr et al. (2016)	Terminal	Lo, BF & RM	Eco	DES	Investigating the efficiency of adopting the existing railway sidings to provide multimodal terminals	Austria	Woody biomass	Biofuel
Väätäinen et al. (2017)	Terminal	Lo, BF & RM	Eco	DES	Evaluating the performance of the BSC with intermediate terminals at different distances.	Finland	Forest chip	Heat & power
Fernandez-Lacruz et al. (2019)	Terminal	BF & RM	Eco	DES	Evaluating the efficiency of terminals in supplying biomass to CHP and biorefineries with varying sizes	Sweden	Woody biomass	Heat & power
Enström et al. (2021)	Terminal	BF & RM	Eco	DES	Evaluating the performance of the BSC with intermediate terminals at different distances.	Sweden	Wood chips	Biofuel
Khoddami et al. (2021)	Hub	BF	Eco	System dynamics	Comparing coordination strategies of quantity discount and cost-sharing to coordinate the BSC with hubs	Canada	Wood pellet	Electricity
Kühmaier et al. (2014)	Terminal	Lo	Eco & Env	AHP & fuzzy set theory	Determining the most suitable areas for energy wood storage terminals	Austria	Woody biomass	
How and Lam (2017)	Hub	Lo	Eco	AHP & PCA	Determining the most suitable areas for hubs	Malaysia	Agricultural residues	
Lemire et al. (2019)	Depot	Lo, CP & BF	Eco	AHP, GIS & software-based optimizer	Determines the suitable locations, allocations, sizing, and number of depots according to different demand location scenarios.	Canada	Corn stover	Cellulosic sugar
Muerza et al. (2023)	IBLC	SS & PP	Eco, Env & Soc	AHP, TOPSIS, DES & agent-based simulation	Evaluating the economic and environmental feasibility of implementing IBLCs with a focus on purchase problem of agricultural residues	Spain	Wheat straw residuals & wood chips	Wood pellet

Eco: Economic, **Env:** Environmental, **Soc:** Social, **Lo:** Location, **BF**: Biomass Flow, **CP:** Capacity Planning, **PP:** Production Planning, **RM:** Resource Management, and **SS:** Supplier Selection.

concluded that utilizing a mobile pyrolysis system can reduce the costs of handling and transporting raw biomass, allow access to remote areas, and withstand adverse weather conditions. Additionally, when dealing with small-scale plants, they recommended implementing a decentralized system because of its portability and ability to reach remote areas. Liu and Bao (2019) suggested adopting the pre-treatment technology of dry acid in depots due to its advantages of zero wastewater generation. This technology leads to the higher collection of feedstock and consequently upscaling the biorefinery operations for bioproduct production. Recently, Lan et al. (2021) investigated the technological and economic aspects of distributed preprocessing systems within the context of fast pyrolysis biorefineries. They examined several SC configurations with various biomass blending ratios and different biorefinery and preprocessing sites, as well as alternative preprocessing technologies.

LCA is a systematic way of evaluating the environmental impact of a product, process, or service from its extraction of raw materials to its disposal. (Vazifeh et al., 2023a). LCA considers resource use, emissions, and waste generation, providing a comprehensive analysis to guide more sustainable decision-making (de la Fuente et al., 2018; Sadaghiani et al., 2023). Using this approach, Nguyen et al. (2014) conducted a study to investigate the impact of the location and size of preprocessing depots on GHG emissions from agricultural residue logistics. To this end, they compared two location scenarios. In the first scenario, they considered equally distributed depots within the vicinity of counties that have access to high biomass supply density. In the second one, they determined locations with the shortest rail transport distance to the biorefinery while considering proximity to high-supply counties. Results showed the benefit of locating depots near direct railroad lines because this type of transportation has the lowest costs with better environmental performance. In another study, Dias (2014) assessed the environmental impact of roadside chipping of loose residues, terminal chipping of loose residues, and terminal chipping of bundled residues in fuel chip production. The main aim was to identify the SC configuration and machinery bringing the least environmental impact. They concluded that regardless of what equipment is used, roadside chipping of loose residues has less impact. While in terminal chipping configurations, it depends on the machinery type and distances travelled between the forest and the power plant. Regarding LCA of mobile production systems in pelletizing logging residues, de la Fuente et al. (2018) concluded that using the Swedish grid-based electricity mixes instead of stand-alone diesel-based electricity in the terminals has the potential to mitigate the environmental effects associated with this process. In another study, Kim et al. (2019) evaluated the environmental impacts of integrating a decentralized (depot-based) biorefinery with a coal-fired power plant. They demonstrated that utilizing biomethane and residual solids in the depot-based systems results in significantly lower biofuel selling prices compared to conventional centralized biorefineries. According to Lan et al. (2020), incorporating preprocessing depots reduces the energy consumption of biorefineries while increasing the overall life cycle energy and global warming potential. However, these findings are specific to their case study of blended feedstock (i.e., pine residues and switchgrass) utilization. The suggestion was made that environmental impacts could be reduced by raising the proportion of switchgrass, given that energy consumption at the depot is primarily influenced by the higher moisture content of pine feedstock.

4.3. Case studies in bio-hub implementation

In addition to modeling approaches, the literature was analyzed in terms of their case study regions. The distribution of case studies on bio-hub implementation in the context of the BSC across different regions (i.e., 13 countries) reveals an interesting pattern providing valuable insights into the global landscape of this sustainable initiative. North America stands out with a substantial representation, comprising 61% of cases, of which 43 cases are in the USA and 11 cases in Canada (See Table 7). The higher concentration of bio-hub implementation case

Table 6
Summary of systematic modeling applications in bio-hub implementation problems.

Authors (year)	Bio-Hub Term	Problem	Sustainability Pillar	Modeling Approach	Aim	Case Study	Feedstock Type	Final Bioproduct Type
Muth et al. (2014)	Depot	PE	Eco & Env	TEA	Analyzing the effects of distributed preprocessing supply system and conventional supply system designs in terms of cost and environmental sustainability	USA	Woody biomass	Bioethanol
Lamers et al. (2015a)	Depot	TS	Eco	TEA	Analyzing different depot configurations to compare the possibility of adopting sophisticated pre-treatment technologies	USA	Corn stover & woody biomass	Bioethanol
Liu and Bao (2019)	Regional biomass collection depot	TS	Eco	TEA	Evaluating the efficiency of adopting dry acid pre-treatment technology in depots	China	Agricultural residues	Bioethanol
Patel et al. (2019)	Mobile pyrolysis system	TS	Eco	TEA	Evaluating the technical and financial viability of switching from centralized to decentralized pyrolysis units	Canada	Woody biomass	Bio diesel
Lan et al. (2021)	Depot	Lo & TS	Eco	TEA	Evaluating several supply chain configurations with various biomass blending ratios and different biorefinery and preprocessing sites, as well as alternative preprocessing technologies.	USA	Forest residues & switchgrass	Gasoline & bio diesel
Dias (2014)	Terminal	PE	Env	LCA	Evaluating the environmental impact of roadside chipping of loose residues, terminal chipping of loose residues, and terminal chipping of bundled residues	Portugal	Eucalypt logging residues	Fuel chips
Nguyen et al. (2014)	Depot	Lo & CP	Env	LCA	Evaluating the impact of location and size of preprocessing depots in GHG emissions from agricultural residue logistics.	USA	Corn stover	Bioethanol
de la Fuente et al. (2018)	Terminal	PE	Env	LCA	Evaluating environmental profiles of woody pellets production from logging residues in terminal-based and land-based scenarios	Sweden	Woody biomass	Wood pellet
Kim et al. (2019)	Depot	PE	Eco & Env	LCA	Evaluating the environmental impacts of integrating a decentralized (depot-based) biorefinery with a coal-fired power plant.	USA	Corn stover	Biomethane
Lan et al. (2020)	Depot	PE	Env	LCA	Evaluating the life-cycle primary energy consumption and global warming potential of alternative biorefinery systems with and without a decentralized depot	USA	Pine residue & switchgrass	Gasoline & bio diesel
Toba et al. (2023)	Depot	Lo	Eco & Env	Graph Theory & K-means clustering	Determine the most suitable areas for depots	USA	Agricultural residues & energy crops	Bioenergy
Lamers et al. (2015b)	Depot	PE	Eco	Financial analysis	Calculating and comparing the total cost of the conventional supply system and advanced supply system with depot	USA	Corn stover & woody biomass	Bioethanol
Virkkunen et al. (2016)	Terminal	PE	Eco	Financial analysis	Analyzing terminal cost for forest fuel supply	Finland	Woody biomass	Biofuel
Berg and Athanassiadis (2020b)	Terminal	PE	Eco	Financial analysis	Evaluating the procurement cost of biomass supply to a potential biorefinery with different terminal configurations	Sweden	Forest residues	
Martinkus et al. (2018)	Depot	Lo	Eco	Financial analysis coupled with decision matrix	Determining the most suitable areas for depots	USA	Agricultural residues	Biofuel
Han et al. (2021)	Depot	PE	Eco	Financial analysis	Evaluating year-round storage operation of three agricultural residues under dry acid pre-treatment method at regional collection depots	China	Agricultural residues	
Kim et al. (2018)	Depot	PE	Eco & Env	Descriptive statistics	Evaluating the efficiency of a depot-based decentralized biorefinery system in the energy independence and security act compliant bioethanol production	USA	Agricultural residues	Bioethanol

Eco: Economic, **Env:** Environmental, **Lo:** Location, **CP:** Capacity Planning, **TS:** Technology Selection, and **PE:** Performance Evaluation.

Table 7
Frequency of case study region, biomass, and bioproduct types in the reviewed literature.

Case Study	Frequency	Feedstock Type	Frequency	Bioproduct type	Frequency
North America	55	Agricultural Residues	43	Biofuel	54
Asia	15	Forest-based Biomass	42	Electricity (Power)	11
Europe	14	Energy Crops	17	Bioenergy	3
Not Specified	6	Livestock waste	4	Heat	4
		Municipal Waste	3	Bio-Chemicals	1
		Algae	2	Not Specified	20
		Not Specified	4		

studies in the USA can be due to several factors, such as vast biomass resources and comparatively high annual production of forest and agricultural products.

. The diversity and abundance of biomass feedstock available across different regions of the country enhances the applicability and adaptability of these hubs (Nicholls et al., 2022). Moreover, the scale and diversity of the USA markets, in terms of both geographical distribution and industrial sectors, provide ample opportunities for bio-hub implementation. Different regions may have unique biomass resources and logistical challenges, prompting the exploration of diverse bio-hub models tailored to specific market demands. Moving to Europe, almost 16% of case studies have contributed to the literature, with six originating from Sweden and two from Finland. Similarly, in Asia, around 16% of case studies shed light on the bio-hub landscape, with China contributing seven cases. Although these studies have been customized to specific regions, considering the distinctive challenges and opportunities in bioenergy, their findings can be applied in other jurisdictions to highlight key considerations for successful bio-hub implementation. It is worth mentioning that having a suitable research infrastructure has played an important role in publishing studies in the indicated countries. However, the main aim is to apply insights earned from bio-hub incorporation across diverse regions and inform future research in areas with similar characteristics, facilitating knowledge transfer and stimulating creative thinking in this field.

These studies were analyzed based on the type of feedstock and the final bioproduct under investigation summarized in Table 7. The choice of feedstock may be influenced by some factors, such as regional factors (e.g., biomass yield and adaptability to different climate conditions and soil quality), economic factors (e.g., feedstock price and production cost), and the conversion rate to bioproduct (Mottaghi et al., 2022). According to this Table, forest-based biomass and agricultural residues have been of special interest when bio-hubs are integrated within a BSC (i.e., 47% of papers). This may be due to their abundance and practical applications in BSCs. The utilization of energy crops is represented by 18% of studies, likely due to various influencing factors. Energy crops such as switchgrass often require dedicated cultivation efforts and might have associated challenges, such as land use considerations and potential competition with food crops (Zahraeec et al., 2020). As such, researchers may be interested in initially exploring feedstock that is more readily available or has fewer associated complexities than energy crops. These statistics were followed by livestock waste with four cases, municipal waste with three cases, and algae with two cases, while the rest of papers did not explicitly mention the specific feedstock under examination. Moreover, Fig. 7 illustrates that 70% of the papers investigated a single type of feedstock rather than multi-feed stock (i.e., 25%). However, given the total number of papers published each year, it appears that research on multi-feedstock studies is still emerging. Indeed, bio-hubs provide an opportunity to store a diverse array of feedstock types, each with varying availability throughout the year. These facilities can preprocess feedstock and produce uniform-format stable products, which enables effective management of potential supply disruptions arising from weather conditions and seasonal fluctuations in biomass availability (Hossain et al., 2024).

Taking the final bioproduct into account, the studies were classified into biofuel (i.e., bioethanol, bio methanol, gasoline, biodiesel, biogas, and solid fuel like pellets), electricity (i.e., power), heat, and bio-chemicals. However, some studies have not distinctly specified the type of bioenergy, so the term “bioenergy” was employed to encompass these studies. Among the final products, the exploration of biofuel production is the center of academic research (i.e., 60%), while electricity and heat production have been less studied. Moreover, around 20% of the literature has not specified the bioproduct type.

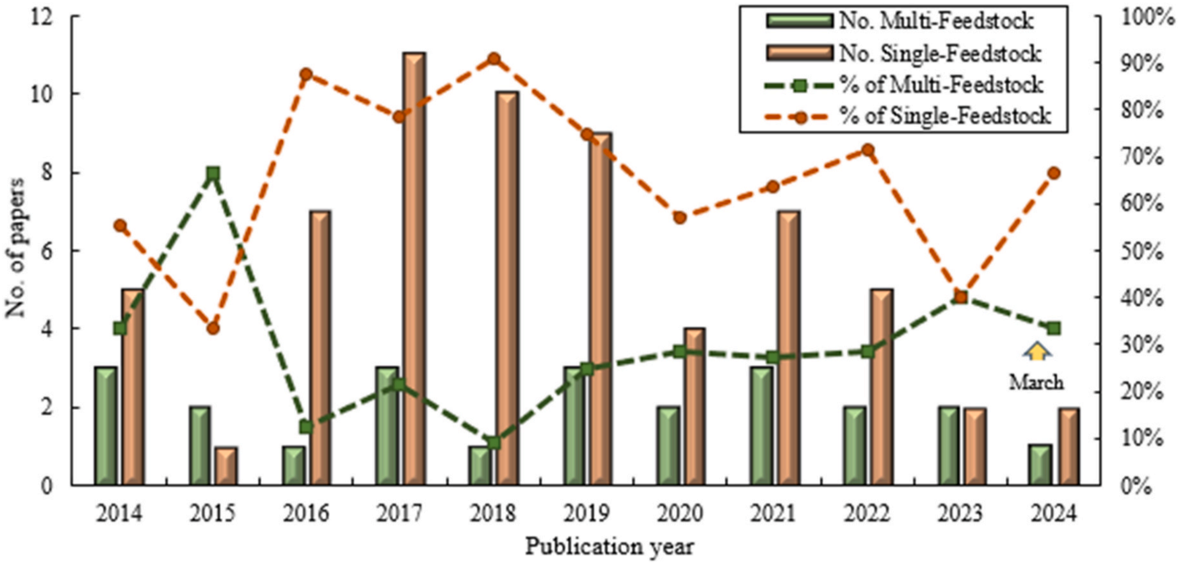

Fig. 7. Distribution of published peer-reviewed journal papers dealing with single and multi-feedstock.

Approximately 90% of the case studies have concentrated on a single specified final bioproduct. This could be attributed to the complexity that arises in dealing with multiple feedstocks and end products, which leads to computationally time-consuming problem-solving on a large scale (Mottaghi et al., 2022). However, in Lan et al. (2020, 2021), and Gautam et al. (2022), authors have investigated the possibility of producing different bioproducts using multi-feedstock sources.

5. Policy aspects and government programs

Up to this point, the focus of the review has been primarily on academic studies published in peer-reviewed journals. However, it is essential to acknowledge the existence of valuable research originating from government programs and national laboratories concerning bio-hubs and their operations. These studies illustrate the engagement and support of several countries in advancing bio-hub projects. To ensure a comprehensive literature review and gain insights from policymakers' perspectives, this section discusses the technical reports published by government agencies.

A noteworthy example is the Finnish-Swedish project, 2019, which was dedicated to the development of a bio-hub model. This project assessed the business and operational structure of forest biomass terminals, aiming to improve their ability to serve conventional forest sectors and emerging biorefining industries. According to the results of this work, the created bio-hub model, which was adopted by the Bastuträsk terminal in Northern Sweden, could provide practical information on business plans for terminal entrepreneurs. Moreover, this model could offer insights into i) assessing raw material availability and selecting an appropriate terminal location, ii) designing terminals and improving operational efficiency, and iii) raw material treatment strategies in terminals. The researchers transformed the bio-hub model into a web-based tool to assist stakeholders in making informed decisions.

Furthermore, under IEA bioenergy Task 43, several projects on bio-hub have been conducted around the globe with the aim of quantifying the value of bio-hubs. In a collaborative project conducted by IEA and Natural Resources Canada in 2020, a SWOT analysis was done to understand strengths, weaknesses, opportunities, and threats for existing or potential bio-hubs in Canada. In this project, stakeholders and partners from across Canada were asked to investigate strategies for successfully establishing and implementing bio-hubs in different regions to enhance the Canadian bioeconomy. According to the results published in their report (Nasso et al., 2020), the availability of sustainable biomass, maintaining the quality and quantity of feedstock and access to a highly skilled workforce were identified as the main strengths in the biomass sector in Canada that could help promote bio-hub projects. They identified the potential opportunities afforded by bio-hub implementation to use underutilized feedstock and engage non-traditional players in bio-based projects. However, they concluded that the limited access to capital investment and the complexity of intergovernmental structures and priorities may hinder bio-hub implementation in Canada. Furthermore, various sources of uncertainty, such as weather conditions, policy support, and market fluctuations, as well as a lack of trust stemming from past failures in bio-economy projects, could pose significant threats to bio-hub implementation initiatives.

Another research project was conducted in Australia (IEA Bioenergy Task 43) to examine the viability of bio-hubs in Southeast Queensland, Australia. The study analyzed the availability of biomass in private native forests and assessed the viability of establishing bio-hubs at both local and regional levels to produce value-added products. Additionally, an economic analysis of two proposed bio-hub scenarios was conducted: one aimed at biochar production, and the other focused on pellet production. The analysis considered factors such as biomass resources, supply chain costs, and regional market dynamics to determine the financial and operational feasibility of the bio-hubs (Berry, 2022).

In another project under Task 43, Pradhan et al. (2022) conducted a TEA of producing several bioproducts in bio-hubs at certain locations in western, central, and eastern Canada. They studied different pathways of producing forest-based bioproducts within Canadian bio-hubs in terms of their economic feasibility. More recently, Rai and Monaghan (2024) analyzed the environmental sustainability of bio-hubs in Ireland using LCA. In their report, they investigated three sample bio-hub scenarios: i) A bio-hub that converts post-harvest agricultural residues in Croatia to solid fuel pellets used in distant domestic heating, ii) A bio-hub that converts forest residue in Ireland to gaseous biofuel to power an Irish timber truck fleet, and iii) A bio-hub that converts forest residue, also in Ireland, to crude bio-oil, which is then transported to an oil refinery to produce lower-carbon diesel. They calculated GHG reductions of 90% for the first and second bio-hubs and 62% for the third one.

In addition to the IEA, the Bioenergy Feedstock Library of the US published a report to provide a survey of the publicly available analytical data about the biomass feedstock types and different equipment used for feedstock preprocessing in the US. In this report, researchers discussed the importance of preprocessing operations in successfully implementing bioenergy projects, particularly at large-scale production levels (Emerson et al., 2023). The Idaho National Laboratory asserted that feedstock preprocessing in depots for densification can reduce moisture content through a drying process, consequently lowering associated storage and transportation costs (Jacobson et al., 2014).

6. Discussions and future research directions

Reviewing the literature, including scientific papers and technical reports, revealed that the developing bioeconomy is in need of adopting practical strategies to make residues and by-products available in accessible locations and at lower costs (Hossain et al., 2024). Incorporating bio-hubs within networks offers an opportunity to reduce the risk of feedstock shortage, facilitate transportation activities, benefit from economies of scale, and consequently reduce the total cost of the network (Nur et al., 2021). As the literature illustrated, scholars have tried to focus on investigating certain aspects of bio-hubs that can contribute to making them a viable and sustainable solution in practice. Although some important aspects have been studied, there are still critical gaps that necessitate further exploration in this area. This section presents and discusses potential research directions from BSC and modeling perspectives.

6.1. Analyzing findings from the BSC perspective

As indicated by the results, the selected papers have predominantly concentrated on the strategic decision of bio-hub design, mainly location selection along with biomass flow planning (i.e., 72%), and in some cases (i.e., 22%), capacity planning of bio-hubs (See Fig. 8). However, these strategic decisions might be impractical or infeasible at tactical and operational levels (Akhtari and Sowlati, 2020). For instance, when biomass flow is planned at the strategic or tactical level, the quantity of biomass transshipped to (from) bio-hubs might not be enough to meet the daily demand of the other facilities (Akhtari et al., 2018). To prevent such problems, future studies can aim at developing integrated models to ensure the feasibility of establishing bio-hubs while addressing operational level variabilities, such as demand and lead time (Jazinaninejad et al., 2022).

Furthermore, the findings from our review revealed that the technical aspects of bio-hubs have not been sufficiently studied. According to Tables 4–6, bio-hubs were mostly considered as an intermediary point to facilitate storage and logistical activities. However, as depicted in Fig. 2, various pathways can be pursued to produce multiple products for further processing or end-uses, depending on the type of feedstock available (Pradhan et al., 2022). Different regions may have varying availability and suitability of biomass resources, ranging from agricultural residues and energy crops to forestry residues (Mottaghi et al., 2022). By leveraging this diversity and decreasing the reliance on a

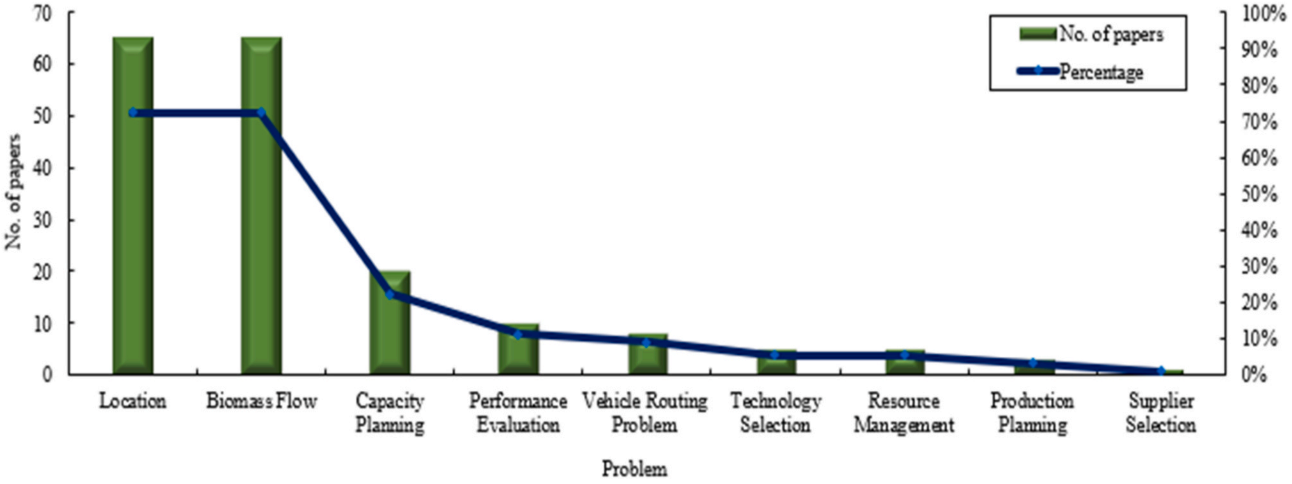

Fig. 8. Studied problems in the literature of bio-hub implementation in BSCs.

single feedstock, bio-hubs introduce an interesting avenue for investigating the use of multiple sources of feedstock to produce different outputs such as power (i.e., electricity), heat, biofuel, bio-chemicals, and biomaterials (Nasso et al., 2020). Razm et al. (2023) demonstrated the potential of utilizing multi-feedstock to diversify the product range of biorefineries, allowing them to match energy demand fluctuations. Although their BSC initially focused on electricity generation, storage limitations prompted the consideration of simultaneous biofuel and electricity production. In this work, biofuel was supposed to be stored for subsequent conversion into bioenergy. Therefore, by increasing the availability of a uniform-format stable feedstock, the resilience of BSCs against seasonal variations and weather fluctuations can be increased (Kulišić et al., 2019; Lan et al., 2021; Hossain et al., 2024). In this scenario, optimizing production planning (Muerza et al., 2023), technology selection (Liu and Bao, 2019; Patel et al., 2019), and resource management (Fernandez-Lacruz et al., 2019; Enström et al., 2021) within bio-hubs becomes imperative. Additionally, future research can examine the optimization of bio-hub ordering practices to ensure the timely fulfilment of biorefinery demands (Nguyen and Chen, 2022). Such decisions could enhance the overall effectiveness and adaptability of BSCs, leading to improved operational performance and sustainability (Jazinaninejad et al., 2022).

The literature review also highlighted the importance of biomass quality in the context of the BSC as feedstock. In particular, agricultural and forest residues exhibit high-quality variability (Sokhansanj et al., 2006). The quality, which is defined by moisture and ash contents, can have a significant impact on the design and management of the BSCs (Aboytes-Ojeda et al., 2022a). Considering biomass quality and associated cost parameters can lead to different BSC topologies (e.g., location and number of facilities) and transportation paths (Castillo-Villar et al., 2017). Moreover, biomass is considered a unique perishable product undergoing continuous degradation and is unlike other perishable products that have predetermined shelf lives. Indeed, the deterioration of biomass depends on several factors (e.g., storage and preprocessing methods, type of feedstock, and moisture content). As such, biomass yield decreases over time as a result of ageing of feedstock in storage (Razm et al., 2023). Despite its crucial significance, most studies have overlooked this characteristic of biomass in decision-making processes to simplify their proposed models. Therefore, it is vital to explore the variability in feedstock quality and degradation rate when making strategic and tactical/operational decisions regarding bio-hubs. Furthermore, it was revealed that different sources of uncertainty (e.g., policy support, market fluctuation, and technical errors) and disruption risks (e.g., natural disasters and impact) pose significant threats to the successful implementation of bio-hub projects (Liu et al., 2017; Abasian et al., 2019). Such failures can reduce investors' confidence and deter similar projects from being launched (Nasso et al., 2020). Therefore, future studies are needed to explore ways of designing resilient bio-hubs while considering potential uncertainty factors.

The content analysis illustrated that most of the BSC networks proposed by scholars are either centralized or decentralized. Centralized networks may suffer from bottlenecks and delays due to reliance on a single decision-making point. While decentralized networks may struggle with coordination and consistency issues across multiple nodes as well as high operational costs (Ahlqvist et al., 2022). In practice, each actor seeks to optimize their individual outcomes, which may potentially conflict with the objectives of others (Mafakheri et al., 2021). For example, bio-hubs aim to minimize their total cost, while suppliers seek to maximize their profits from selling feedstock to these hubs. According to IEA, one of the potential challenges in fostering bio-hub implementation is the lack of frameworks to incentivize end-users to use more bioproducts and motivate stakeholders to invest in bio-based industries (Kulišić et al., 2019; Nasso et al., 2020). To address all these challenges, coordination mechanisms such as quantity discount, risk sharing, cost sharing, and profit sharing can be implemented to create a trade-off between the objectives of individual actors and improve the performance of the whole BSCs.

To ensure that bioenergy serves as a sustainable alternative to fossil fuels, comprehensive assessments of economic, environmental, and social aspects (i.e., sustainability pillars) become crucial, especially when introducing new facilities (e.g., bio-hubs), technologies, or equipment into a BSC (Jazinaninejad et al., 2022; Mottaghi et al., 2022). As Fig. 9 demonstrates, the most studied sustainability pillar regarding bio-hub scenarios was the economic aspect (e.g., investment, transportation, inventory, and preprocessing costs), studied in 76% of the papers. However, environmental and social effects of bio-hub incorporation have been examined in only a few studies, despite their significance (See Fig. 9). Operating these facilities can result in large-scale production of biomass, collection, transportation, and adoption of preprocessing conversion technologies, leading to environmental impacts (Lan et al., 2020; Toba et al., 2023; Rai and Monaghan, 2024). While bio-hub implementation can stimulate the local economy and social indicators by creating jobs in transportation, operation, and construction sections, environmental indicators like land use, soil quality, and water utilization may pose challenges (Nicholls et al., 2022). Therefore, future endeavors should focus on developing multi-objective models to navigate trade-offs among the three sustainability pillars.

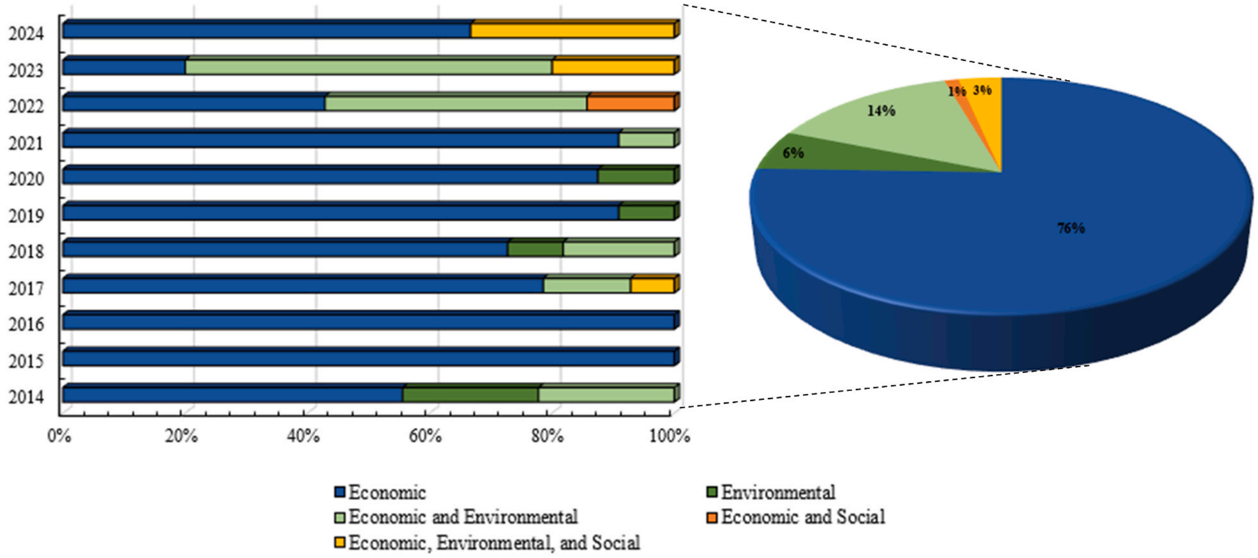

Fig. 9. Sustainability pillars of bio-hub implementation in BSCs.

6.2. Analyzing findings from the modeling perspective

Given the modeling approaches, the results of the analyses demonstrated the widespread application of mathematical programming in addressing bio-hub implementation challenges within BSCs. This can be attributed to its ability to provide optimal decisions for bio-hub designing and planning. However, there are key areas that warrant further exploration. In terms of modeling uncertainties, the literature predominantly adopts a two-stage stochastic modeling approach, which proposes a known probability distribution for uncertain parameters. Decomposition-based methods and heuristic and metaheuristic algorithms have been employed in the literature to solve these problems. However, as the number of uncertain parameters increases, the computational complexity increases significantly (Mavromatidis et al., 2018). Approaches like robust optimization and relatively newer ones, such as ML and simulation techniques, offer promising directions for exploration, especially in scenarios where there is limited and imprecise parameter information (Habibi et al., 2023). Robust optimization proves valuable in addressing uncertain parameters when their probability distribution function is either unknown or challenging to estimate. The solution of this approach is more reliable and less vulnerable to variations because it considers worst-case scenarios (Behzadi et al., 2017; Kalhor et al., 2023). Leveraging the learning and predictive capabilities of ML approaches allows for their integration with other methods (e.g., mathematical programming) to formulate data-driven approaches (Habibi et al., 2023). Keith et al. (2024) illustrated that ML algorithms (e.g., decision tree, random forest, logistic regression, k-nearest neighbors, and support vector machine) can reduce the computational expensiveness of stochastic programming models and consequently reduce the complexity of these problems. Furthermore, simulation techniques offer insights into the dynamism and uncertainty of operational factors by analyzing interactions among agents. In addition, these techniques can model the impact of external stressors and influencing factors (such as climate conditions, policies, incentives, state of economy, and competition) on the day-to-day operation of a BSC (Groundstroem and Juhola, 2021). As such, implementing such approaches not only enhances the model's capability to handle uncertainty but also facilitates making well-informed decisions that align with real-world scenarios.

In addition to the mentioned directions, government policies can play an important role in scaling up bioenergy production and facilitating bio-hub implementation. Supportive policies have the potential to stimulate and boost investments in bioenergy projects by providing financial incentives, tax credits, or subsidies to such enterprises (Vazifeh et al., 2023b). Consequently, the creation of new demand markets for biomass feedstock and bioenergy is encouraged, fostering the establishment and expansion of bio-hubs. Therefore, there is a need for a quantitative analysis of the impacts of policies and regulations on bio-hub implementation. In this regard, system dynamics simulation can offer a macro-level analysis for decision-makers. Furthermore, methods like game theory can assess the strategic interactions between policymakers and other stakeholders, aiding in the identification of policies that lead to mutually beneficial outcomes and effectively coordinating an entire BSC (Vazifeh et al., 2023c).

7. Conclusions

Literature review in the context of BSCs demonstrates that decision-making processes of preprocessing and storage facilities, such as bio-hubs, have attracted less attention compared to other players' problems (e.g., suppliers and conversion facilities). Although this trend shows a positive development, there is still much room for improvement. Recognizing the significance of bio-hubs in BSCs underscores the critical need to delve deeper into this aspect. They enable better resource utilization, promote circular economy principles, and reduce the environmental footprint associated with biomass logistics. Hence, these hubs could contribute to the overall resilience of the BSCs and ensure a more sustainable and cost-efficient approach to bioenergy production.

This literature review aimed to address the existing research gap by exploring the multifaceted aspects of bio-hubs, as well as the advantages, challenges, and opportunities associated with their implementation. Following the five-step guideline proposed by Denyer and Tranfield (2009) for SLR resulted in the identification of 90 relevant papers published within the last ten years. A meticulous analysis and categorization of these studies was conducted to explore their limitations and offer potential research directions. The findings revealed a predominant focus among researchers on the design of bio-hubs, particularly in determining their optimal locations using mathematical programming models. Given that biomass supply and bioproduct demand areas are typically not located close to each other, determining the strategic location of bio-hubs is critical. Although the selected papers give valuable insight into the problem under investigation, some important aspects have been given limited focus or have been overlooked.

It is recommended to investigate tactical and operational level decisions, such as resource management, inventory, and production planning within bio-hubs along with strategic decisions. Furthermore, to accurately capture the dynamic and uncertain nature of the BSC, it is essential to integrate various sources of uncertainty and account for biomass degradation in the decision-making process. Additionally, examining the impact of coordination strategies and government policies on the performance of bio-hubs and BSCs presents a compelling avenue for future research. Consideration of environmental and social aspects in the implementation of bio-hubs, coupled with economic criteria, is also recommended to enhance the competitive advantages of bioproducts. From the modeling viewpoint, powerful approaches, like ML and simulation models, can be applied either individually or in combination to address such complex and dynamic problems. It is worth mentioning that the present study concentrated on quantitative approaches for analyzing bio-hub implementation within BSCs, excluding empirical studies. As such, prospective researchers are encouraged to explore qualitative techniques, such as questionnaire-based or interview-driven empirical studies, to capture subjective experiences and stakeholder perspectives in this field.

CRediT authorship contribution statement

Mahsa Valipour: Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Fereshteh Mafakheri:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition, Conceptualization. **Bruno Gagnon:** Writing – review & editing, Validation, Resources, Conceptualization. **Robert Prinz:** Writing – review & editing, Validation, Resources, Conceptualization. **Dan Bergström:** Writing – review & editing, Validation, Resources, Conceptualization. **Mark Brown:** Writing – review & editing, Validation, Resources, Conceptualization. **Chun Wang:** Writing – review & editing, Supervision, Resources, Conceptualization.

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.

Data availability

Data will be made available on request.

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