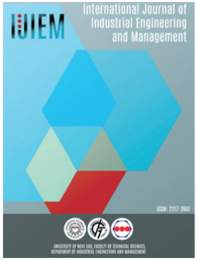
ISSN 2683-345X
journal homepage: http://ijiemjournal.uns.ac.rs/



International Journal of Industrial Engineering and Management

Volume 14 / No 3 / September 2023 / 244 - 256

Original research article

Residual Forestry Biomass Supply Chain: A Mapping Approach

P. Rijal[a], P. Bras[b], S. Garrido[c], J. Matias[a,d], C. Pimentel[d,e], H. Carvalho[f,g,*]

[a] *University of Aveiro, Department of Economics, Management, Industrial Engineering and Tourism (DEGEIT), 3810-193 Aveiro, Portugal;*

[b] *Department of Mechanical and Industrial Engineering, NOVA School of Science and Technology, Universidade NOVA de Lisboa, 2829-516 Caparica, Portugal;*

[c] *CeBER R&D Center, Faculty of Economics, University of Coimbra, Av Dias da Silva 165, 3004-512 Coimbra, Portugal;*

[d] *GOVCOPP R&D Center, University of Aveiro, 3810-193 Aveiro, Portugal;*

[e] *University of Minho, Production and Systems Department and Algoritmi Research Unit, 4800 - 058 Guimarães, Portugal;*

[f] *UNIDEMI, Department of Mechanical and Industrial Engineering, NOVA School of Science and Technology, Universidade NOVA de Lisboa, 2829-516 Caparica, Portugal;*

[g] *Laboratório Associado de Sistemas Inteligentes, LASI, 4800-058 Guimarães, Portugal*

ABSTRACT

The use of biomass as a renewable resource has gained significant attention in recent years due to concerns about climate change and the need for more sustainable energy and materials. Visualizing the residual forestry biomass supply chain allows for identifying opportunities and challenges related to feedstock harvesting, availability, and transportation costs. This research aims to suggest a map for the valorization of the residual forestry biomass supply chain to identify better and understand the material, financial, and informational flows and to give important insight into the economic dimension of its valorization (costs) and challenges. To attain this objective, two exploratory case studies were conducted. The findings of this research reveal similarities in material flow between a large and small company but a significant difference in transportation expenses. The study also found that farmers and forest owners have a small bargaining power to influence the price of the residues they sell. Therefore, this research contributes to a better understanding of the residual forestry biomass supply chain, enhancing the importance of supply chain maps in overcoming possible bottlenecks and challenges in this sector.

ARTICLE INFO

Article history:

Received April 10, 2023
Revised July 15, 2023
Accepted July 20, 2023
Published online August 1, 2023

Keywords:
Forestry residues;
Biomass;
Supply chain mapping;
Case studies

*Corresponding author:
Helena Carvalho
hmlc@fct.unl.pt

1. Introduction

Forest residues, such as branches, twigs, tree stubs, trunks, bark, and leaves, are a potential source of biomass that can be sustainably harvested and used as feedstocks to produce energy, biofuels, bioplastics, and other bio-based products [1]. Reducing woody residues from forests can also significantly reduce the risk of wildfires [2].

However, since these woody residues have little or no monetary value, their valorization process should be cost-efficient along the Supply Chain (SC) (i.e., from harvesting residual biomass, collection, transportation, and storage to their conversion process distribution to consumers) [3]. Multiple stakehold-

Published by the University of Novi Sad, Faculty of Technical Sciences, Novi Sad, Serbia.

http://doi.org/10.24867/IJIEM-2023-3-336

ers, like forest and farm owners, loggers and logging companies, and biofuel and energy producers, are involved in the valorization process of this type of biomass [4]. Together, these entities form the residual forestry biomass SC [5]. Braghiroli and Passarini [5] and Garcia Maraver et al. [6] studied the potential of forest residues as an energy feedstock. Regarding the SC, Atashbar et al. [4] examined the SC operations individually, addressing the various types of decision-making and presenting mathematical models mainly to study the efficiency of the operations. On the other hand, information on SC mapping is scarce [7], and it is even more limited regarding the mapping of the residual forestry SC. Furthermore, only a few graphical elements were found in the literature describing a residual forestry biomass SC. The work of Mansoornejad et al. [9] focuses on a scenario-based approach to analyze the SC design for forestry biorefinery operations.

Mapping an SC involves visualizing the various entities and activities involved in the product and resource flows from its origin to its destination. This can include entities from raw materials suppliers, manufacturers, distributors, and end-users. In the case of residual biomass, the SC would consist of the source of the biomass (forestry residues), the collection and transportation of the biomass, any processing or conversion steps that may be required, and the final use of the biomass (e.g., as a feedstock for bioenergy production, as a raw material for bioplastics).

This study aims to suggest a map for the valorization of the residual forestry biomass SC not only to identify better and understand the material, financial, and information flows but also to give important insights into the economic dimension of its valorization (costs) and challenges. Attending to this objective the following research question arise:

RQ: How is a residual forestry biomass SC organized, as well as the respective material and information flow?

To reach the objective and answer the research question, two exploratory case studies focused on the valorization of residual forestry biomass from the exploitation and management of forests was carried out in Portugal. Portugal was chosen for these case studies due to its large forestry area, hot and dry summers, and susceptibility to wildfires. According to previous research, the prevailing anticyclone circulation and thermal low over the Iberian Peninsula intensify winds along the western coast of mainland Portugal, allowing fires to spread quickly [10]. Similarly, there are concerns about forest fires becoming a year-round phenomenon after the January 2022 fire. Studying the residual forestry biomass SC in Portugal can provide valuable insights into how to manage and exploit this biomass sustainably and efficiently, which can ultimately help reduce the risk of wildfires and protect the environment and communities.

In this paper, after the introduction section, a theoretical background is developed, followed by the research methodology presentation. Afterwards, the results are described, and a conclusion is drawn.

2. Theoretical Background

2.1 Residual forestry biomass

Biomass represents a viable solution to lower greenhouse gas emissions and dependence on fossil fuels while reducing the risk of fires [12, 13]. Woody biomass, including residual woody and lignocellulosic forest biomass, has shown potential in the global market as a raw material for energy and polyurethane production [14]. Polyurethane is used to produce adhesives, foams, and other starting products, substitute sugar xylitol, membranes for artificial kidneys, and water purification [15, 16]. For instance, Hamelin et al. [17] show how important residual forestry biomass can be as a feedstock for the European bioeconomy as they found that approximately 8500 PJ (petajoule) of energy per year could be produced from the valorization of residual biomass.

A study conducted by Torreiro et al. [18] found that the pruning from grape vines, kiwi trees, scrub (heather, gorse, broom), and other forest pruning could be used at a larger scale for energy production, concluding that using residual biomass in Portugal and Spain to generate biofuels is feasible. The study of Costa et al. [19] shows that biogas could significantly lower carbon-dioxide emissions while still being financially profitable. However, despite the numerous studies focused on this sector, large-scale implementation, or production of bioenergy products like syngas and biodiesel faces numerous difficulties, mainly because of the high logistics cost and the need for more suitable biomass required to produce energy [19].

Residual forestry biomass is mainly obtained from forest management activities like timber harvest, pruning or thinning and stand regeneration, removal of broken-off or low-quality trees, and wood industries. In this line, and according to [5], there are two main sources of forestry residues: i) forest operations, which generate residues such as branches, leaves, treetops, barks, and broken-off or low-quality trees, and ii) wood industries, producing the following residues: sawdust, planer shavings, bark, end-of-life wood products (e.g., plywood and particleboard). The residual biomass obtained from forest operations is mainly heterogeneous in its lignocellulose composition [5].

Table 1 shows the different types of forest residues from forest operations and wood industries and their valorization types.

2.2 Residual forestry biomass supply chain

The residual forestry biomass SC involves collecting, processing, and distributing residual forestry biomass [24]. It includes various individuals, organizations, resources, and technologies organized across multiple stages [25]. Understanding the SC is crucial for implementing a reliable framework, achieving strategic targets, and ensuring a sustainable SC network [26], as shown in Table 2. Value creation in the SC can be achieved through material, information, and financial flows. However, the residual forestry biomass SC faces several challenges, like as the lack of information and coordination between the actors in the SC, which can slow down the process of converting agroforestry residues into biomass [27]. Another challenge is the high dependence on intensive labor, which may not be available in low-density territories [27]. Over-exploitation of available resources may also lead to practices that go against the principles of sustainable development [27]. The high cost of the SC can also hinder the intensified use of forest residues for energy production [28]. Uncertainty about the nature, amount, and quality of forest residues is another logistical and SC challenge [29]. Natural forest disturbances such as wildfire and insect infestation can also cause unpredictable fluctuations in supply, disrupting long-term procurement plans for delivering feedstock to biorefineries [30]. One way to overcome such hurdles is through SC mapping. The visualization of each process of the SC gives a better view of the problems or challenges. Some studies have found that value creation in the SC can be achieved through a better understanding of the material, information, and financial flows [31]. The use of digital technologies in the SC [32], espe-

Table 1. Valorization of residues from the forestry sector

Forest Residues	Valorization products	References
Wood chips, wood shavings, sawdust	Pulp and paper, particle board, Heat	[5]
Woody pruning residues	Wood vinegar	[20]
Branches, tree stubs, trunks, bark	Lignin—plastics, adhesives, binders	[21]
Pulp from the paper industry	Lignin-Vanillic Acid	[22]
Softwood, hardwood woody residues occurring in nature (woods)	Lignin extraction for chemical production	[23]

Table 2. Entities/Stages of a residual forestry biomass supply chain

Entities/Stages	Description	References
Suppliers	Forest owners and farmers who provide raw materials for the supply chain	[34]
Storage	It is a crucial step in the SC to prevent the deterioration of raw materials. The storage process may involve transporting residues from forests to the storage area and specialized equipment, such as dryers or chippers, to prepare the raw materials for storage.	[35]
Transportation	Modes of transport used to transport raw materials to the storage area and the processing facility are trucks, trains, or ships, depending on the distance, amount of biomass, infrastructure, costs, etc.	[36]
Production	It transforms raw materials into finished goods, including chipping, grinding, or pelletizing biomass. Additional processing or treatment may be required to make it suitable for use.	[37]
Distribution	These entities are responsible for the distribution of the finished goods to customers. This may involve additional transportation and storage. Intermediaries such as traders or brokers may also be applied at this stage.	[39] [40]
Customers	End-users of finished goods, such as power plants or industries. These end users may use biomass to generate energy or produce other products. Specific requirements and expectations of the customers must be met for success.	[41]

cially when it comes to perishables products, in this case, perishable residues, need to be handled with extreme care and agility to decrease the wastage of raw materials [33].

Table 2 gives the characterization of the different stages of the SC. The first stage involves suppliers such as forest owners and farmers who provide raw materials for the SC. The storage stage is crucial to prevent the deterioration of raw materials and may involve transportation and specialized equipment. Different transportation modes, such as trucks, trains, or ships, can be used to transport raw materials to the storage area and processing facility. The production stage involves transforming raw materials into finished goods through processes such as chipping, grinding, or pelletizing biomass. Distribution involves delivering finished goods to customers and may involve additional transportation and storage as well as intermediaries such as traders or brokers. The final stage involves customers who are end-users of finished goods such as power plants or industries. Meeting their specific requirements and expectations is essential for success.

All these stages are necessary for the successful movement of goods from the initial source to the final customer. Understanding these elements and their interactions is essential for SC mapping [34].

2.3 Supply Chain Mapping

SC mapping is the process of creating a visual representation of the flow of goods, services, and information from raw materials to the end customer. The study [8] proposes a mapping approach that considers six SC dimensions (i.e., SC entities, relational links, material flow, information flow, management policies, and lead times) and the respective state variables (Table 3).

A set of characteristics should be addressed in mapping an SC, such as it should be interpretable, recognizable, and designed in an easy-to-disseminate format; it should include standardized icons and conventions such as color-coding, or symbol-coding for processes, flows, and links between organizations and facilities [49]. The advantages of SC mapping are i) it presents accurate and easily understandable information that is also informative enough to aid in SC visibility, analysis, and integration [43], ii) it can be used to identify potential points of failure or inefficiencies, as well as to improve collaboration and communication among SC partners [44], iii) it can assist in addressing emerging challenges such as sustainability, SC cyber security, climate change, and global shortages of critical raw materials [44, 45], iv) for improving SC visibility, resilience and efficiency [26].

Accurate SC maps can also improve a company's efficiency by giving decision-makers a view of the flow of goods and information and allowing them to identify the grey areas and bottlenecks that need more attention for efficiency improvement [46]. SC mapping helps to identify all the players involved in the SC, their location, and the relationships between them [41], improving transparency, communication, and collaboration. Identifying and reducing inefficiencies in the SC will also assist in cost savings by reducing waste [44]. Streamlining the SC and addressing bottlenecks and possible risks can improve delivery times and increase customer satisfaction [43]. SC

Table 3. Dimensions and state variables of the supply chain mapping [8]

Supply chain mapping dimension	State variables
Supply chain entities	Type and number Geographic localization
Relational links	Type of relationship between entities (vertical and horizontal relations)
Material flow	Volume and delivery frequency Transport mode Stock location Number of customers
Information flow	Frequency Type of communication (word of mouth, electronic devices, etc.)
Management policies	Stock type and level Management strategy Number of operations
Lead times	Production and transit lead times

mapping is also essential for SC redesign, improvement [46], and digitalization [41]. Some authors [47, 48] argue that SC maps and SC visibility are closely related concepts essential for controlling SC disruption risks and improving decision-making.

2.4 Residual Forestry Supply Chain Mapping

The SC map of residual forestry biomass will include links and nodes connecting suppliers, storage, transportation, production, distribution, and customers [41]. These links and SC maps represent the flows between different entities and processes. The material flows could be raw materials like wood chips, sawdust, bark, leaves, needles, etc., and the different types of finished goods, such as bioenergy pellets, bioenergy briquettes, biopolymers, and dietary supplements. For example, in a residual forestry biomass SC, there would be links between the suppliers and the storage facilities, indicating the flow of residues from the suppliers to the storage facilities. These links can be represented by arrows, with their direction indicating the flow of materials [25].

Different types of arrows can represent different types of links within the SC. For example, a solid arrow can represent the flow of physical goods, while a dotted arrow can represent the flow of information. This can help illustrate the various types of flow within the SC, as seen in Figure 1. In addition to the direction and type, the size and color of the arrow can also be used to represent different flow attributes, as proposed by MacCarthy et al. [41] and Theodore Farris [46]. For example, a thicker arrow might mean a larger volume of goods or information, while a different color arrow might represent another type of goods or information. This helps to provide a more detailed and accurate representation of the flow within the SC.

The nodes in the map would represent the different entities and processes themselves, such as suppliers, storage facilities, transportation, etc. Each of these nodes has attributes such as the entity's location, the type of entity, the number of goods being handled, the cost associated, and so on [41]. The map would include information about the processes at each node. For example, information about the type of processing used (such as chipping, grinding, or pelletizing) and the type of finished goods produced would be displayed at the production node. It would also include information about logistics and stock at each stage of the SC. This could include information about the type of transportation used, the distance, the cost of transportation, and so on [46].

In addition to the link and nodes, the SC map can include relational links between entities, management policies and lead times, and their state variables [9]. The relational links dimension consists of the type of relationship between the SC entities, such as vertical and horizontal relations between forest landowners, loggers, and consumers (Table 3). Vertical links refer to the relationships between entities that are at different levels of the SC, such as between forest landowners and the loggers that would involve the forest landowners providing the raw materials for the loggers to collect and the loggers providing the harvested biomass to the forest landowners for sale or further processing [49].

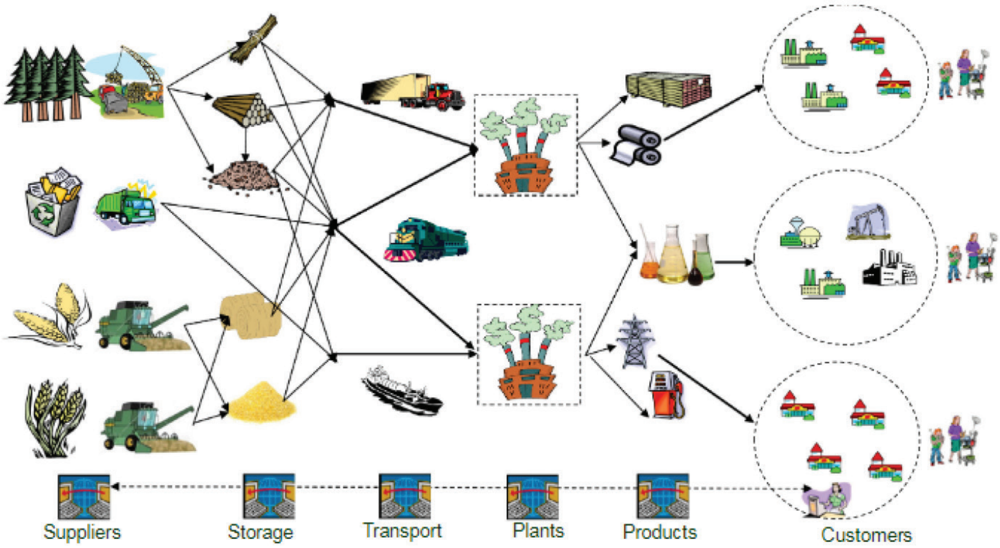


Figure 1. Residual Agroforestry Biomass Supply Chain mapping [9]

Horizontal relations refer to the relationships between entities at the same level of the SC, such as between different forest landowners or different loggers. For example, while other forest landowners may compete to sell their biomass to the same loggers or customers, different loggers may compete to sell their collected biomass to the same customers. These horizontal relationships involve competition and cooperation among the entities at the same level as the SC [50].

The mapping conventions consist of graphical elements representing the SC entities, transportation modes, links, and others, as shown in Figure 2. Regarding residual forestry SC entities, they include:

- Suppliers: The sources of raw materials, which in this case are the owners of the forests that generate residual biomass such as wood, leaves, and other organic matter. This includes forest owners, private landowners, farmers, and state and municipal government entities.
- Loggers: Individuals or companies responsible for harvesting and collecting the residual biomass from the forests. They may also be involved in forest management activities such as pruning.
- Third parties: Companies, organizations, or individuals that provide services to the SC but are not the main entities. These entities may include transportation companies, warehouse services, and providers of specialized equipment such as chippers and balers [49].
- Customers: The entities that use the residual biomass for manufacturing or industrial purposes, such as producing energy polymers, dietary supplements, etc. This may include pretreatment, treatment, and bioenergy and biofuel plants using residual biomass to produce bioenergy or biofuels.

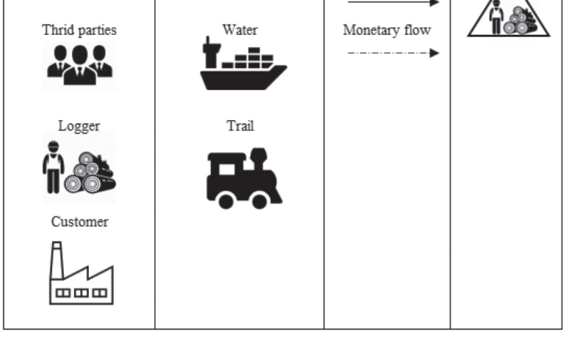


Figure 2. Residual Forestry Biomass Supply Chain Mapping Conventions

3. Research methodology

This study follows a case studies research approach. A case study is an in-depth analysis of a specific case or situation used to explore complex phenomena within their real-life context [50, 51]. Case studies are used in various fields, including agriculture and forestry, to provide rich and detailed data that allows for exploring multiple perspectives and contextual factors [35]. Priya [52] defines exploratory case studies as a research method that aims to investigate a phenomenon to discover facts that can be further investigated in future studies. Using exploratory case studies in this study can help deeply visualize the SC identifying the factors influencing the challenges that farmers and forest owners face. As a result, exploratory case studies are a legitimate research methodology for gaining insights into the residual forestry biomass SC [53, 54].

Understanding the residual forestry biomass SC is especially important in Portugal, where wildfires seriously threaten the forests and surrounding communities. Portugal is the most fire-prone country in Europe, with wildfires destroying an average of 80,000 hectares yearly since 2008. According to [11], understanding the SC for valorizing residual forestry biomass is critical for reducing the risk of future wildfires.

This approach provides rich and detailed data that enables the exploration of multiple perspectives and contextual factors. As emphasized by [50], these two case studies were not intended to test hypotheses but rather to generate new ideas and insights about the research topic and therefore focus on the residual forestry SC. The case studies are based on the upstream SC and the processes involved in getting the raw materials to the manufacturers and producers:

- Case Study 1 focused on a family-run small to mid-sized logging company Logger X, in Portugal. The company's core business is wood trade and forest clearing. Its first-tier suppliers are private landowners who own less than 1 hectare of land. Logger X works with Altri Florestal S.A. to supply feedstocks to biomass power plants. The SC involves forest landowners, Logger X, third parties, and the Altri Florestal S.A.
- Case Study 2, on the other hand, focused on Logger Y, a larger logging firm in Portugal that purchases and sells wood, resins, and sawdust. It sources its feedstock from private forest owners and state-owned institutions. Logger Y

also owns forest land and supplies residues to biomass generation plants. In addition to Altri Florestal S.A, Logger Y sells feedstock to The companies Navigator Company S.A and Casal & Carreira - Biomassa S.A.

Table 4 shows the characterization of the entities in each case study. Because of data confidentiality, the loggers were kept anonymized; they are named Logger X and Logger Y.

These two case studies aimed to identify the role of entities, materials, information, and financial flows in the residual forestry biomass SC using various methods like interviews, observation, content analysis, and survey questionnaires to collect data related to SC entities, links, material and informational flows, policies, and lead times. The data was analyzed carefully to form a comprehensive map based on both residual biomass forestry SC case studies.

4. Results

The results from the two case studies give insight into the economic dimension of the valorization of residual forestry biomass (costs), the daily challenges, and the real-time decisions taken by the SC entities involved in the processes, namely the suppliers, loggers, and third parties. By mapping the cost of collecting, baling, chipping, and transporting, it is possible to identify the number of residual forestry biomass produced in a particular region and the forecasted cost for valorization. The SC map for case study 1 involves forest landowners, Logger X, third parties, and Altri Florestal S.A. It shows the material and information flow along the SC and uses the symbology in Figure 3 to deliver the different entities and flows. From the SC below, it can be noted that forest landowners contact Logger X to sell their wood and have their land cleared. Logger X evaluates the value of the woody residues and offers a price to the landowner. Trees are cut down during harvesting, and logs are separated from branches. Logger X rents equipment for this process from third parties. Logs and branches are gathered for transport, while residual biomass must go through a baling or chipping process. At Altri Florestal S.A's reception park, the cargo's quantity and quality are identified. The price for residual biomass can vary depending on its characteristics.

Meanwhile, Logger Y deals with much larger areas of land and three different suppliers Forest landowners, the State, and CMFF, so they handle the collection and transport of biomass differently. Unlike Logger X, Logger Y uses a GPS Fields Area Measure App to map forest land and calculate the amount of wood available before setting a purchase price. This app helps the company identify different areas: to be evaluated, that have been assessed but not yet exploited, where harvesting has begun, and that have been completed.

For instance, in the case of residues supplied by Figueira da Foz's Municipal Hall (CMFF), CMFF inspects council property to ensure compliance with legislation. If forest residue piles are found, the land-

Table 4. Case studies characterization

	Entity	Role	Description	Location in Portuguese territory
Case study 1	Forest Landowners	Supplier	Small owners of forestry lands	Figueira da Foz
	Logger X	Logger	Forestry company	
	Altri Florestal, S. A	Customer	Pulp and biomass energy company	
Case study 2	Forest Landowners	Supplier	Small owners of forestry lands	Multiple locations in Portugal
	State		State forests from public auctions	
	Municipal Hall of Figueira da Foz (CMFF)		Responsible entity for enforcing the legislation concerning the municipality's forest lands	Figueira da Foz
	Logger Y	Logger	Forestry company	Monte Redondo
	Altri Florestal, S. A	Customers	Company owner of pulp and biomass energy company	Constância / Figueira da Foz / Mortágua / Vila Velha de Ródão
	The Navigator Company		Pulp and paper company	Setúbal / Figueira da Foz / Aveiro
	Casal & Carreira - Biomassa, S. A		Lumber Sawmill Company	Porto de Mós

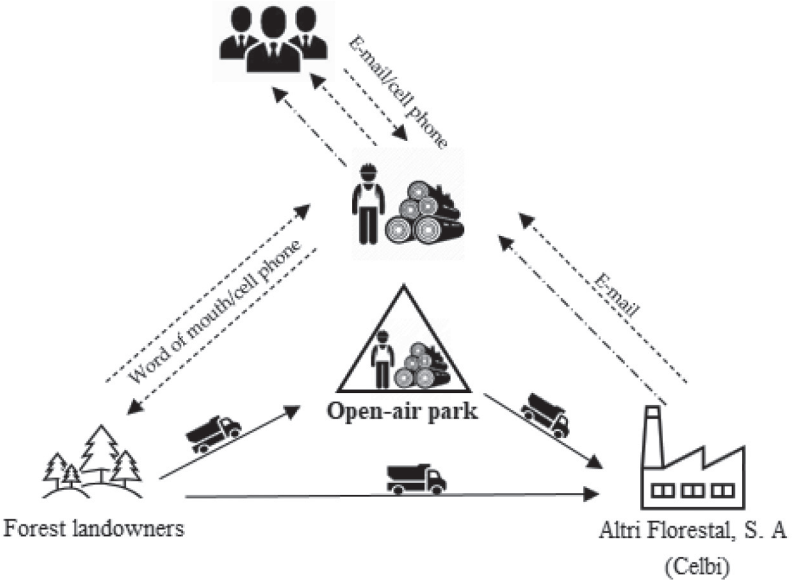


Figure 3. Mapping of the Residual Forestry Supply Chain of Case Study 1

owner is notified and given ten workdays to remove them. If the pile remains after this time and there is more than three m^3 of residues per pile, CMFF pins it in the app, and Logger Y collects and sells the residues to its customers. The total cost of harvesting residues and supplying them to energy and production plants can be calculated like this—Logger Y generally uses 90 m^3 trucks that can carry a load of approximately 20-30 tons in one load. So, the total cost would be between 540€ and 870€ per load if the distance is less than 50 km. Figure 4 shows the SC map of the residual forestry SC of Case Study 2.

After an individual analysis of each case study, a cross-case comment was developed to identify the common and different characteristics of their SCs' maps.

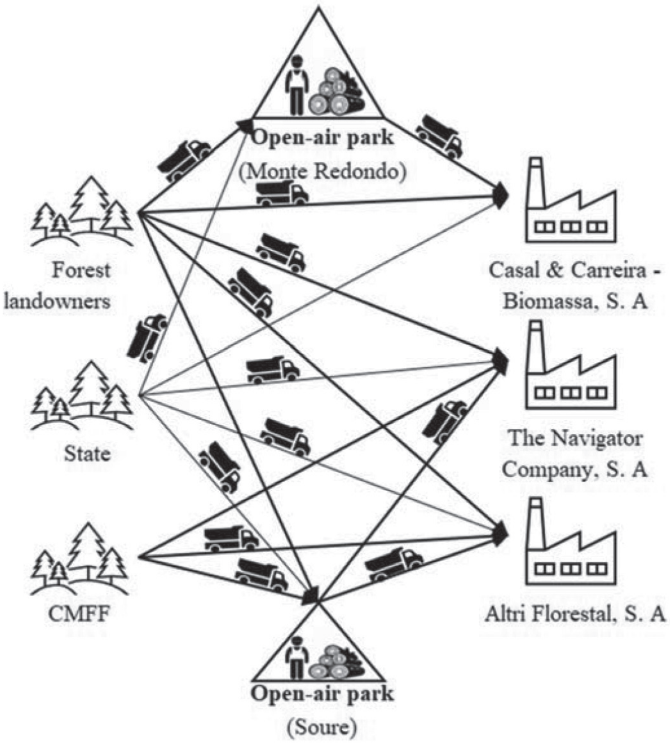


Figure 4. Mapping of the Residual Forestry SC of Case Study 2

Cross-case Analysis

A cross-analysis was carried out to identify similarities and differences in the events, activities, and processes [46] and challenges faced by their SCs to get insights on what main features should be addressed to map residual forestry biomass. Table 5 shows the similarities and differences between the two case studies operations.

Both companies showed similarities in their material flow. However, Logger Y had higher transportation costs as its suppliers are located in different geographic zones of the country. Regarding information flows, Logger Y had a better method of collecting, disseminating, and using the information as he used an App to help him with the data. He communicates with their clients through email, unlike Logger X, which was mainly recording information physically through telephone calls and word of mouth; this could be because Logger X only did business in a relatively small area than Logger Y, and he has only one customer. So, he only requires a little extensive method for the flow of information.

Both case studies showed that farmers and forest owners had low bargaining power regarding residual forestry biomass prices. Due to a lack of knowledge regarding the value of wood residues, private forest owners could not effectively negotiate prices with logging companies. As a result, logging companies could dictate the price of residues by measuring the amount they intended to collect and quoting a price to the forest owners. The forest owners were then left with the option to accept or reject the proposed price.

This raises a serious problem as there is no reference price in the market, and private logging companies exploit farmers and private forest owners, harming them with unfair trade. From the case studies analysis, it was also possible to find that most of the residual forestry biomass collected by these two companies is used in producing energy. Based on the information gathered from both logging companies' SC, it was possible to design an SC map to visually understand the material, economic, and information flows in their SCs (Figure 5).

5. Discussion

In this section, the theoretical and practical implications that were uncovered through the study will be discussed. This discussion focuses mainly on material flows, transportation costs, and the low bargaining power of farmers. Analyzing material flows within the residual forestry biomass SC has several implications for the valorization process. By providing insights into the quantity and distribution of biomass, it enables a better understanding of the available resources for valorization. This material flow analysis fills a gap in the literature by providing insights into the quantity and distribution of biomass. This information can guide decision-making regarding production planning, resource allocation, and investment strategies. Additionally, efficient coordination and synchronization among SC entities are crucial to ensure a smooth and uninterrupted biomass flow from suppliers to customers. Any disruptions or bottlenecks in these

Table 5. Similarities and differences of case studies operations

Operations	Similarities	Differences
Harvesting and Collection	Both loggers have the necessary resources to perform the exploitation of the wood.	The geographic dispersion of Case Study 2 is more significant than in Case Study 1. Therefore, Logger Y has more resources (equipment and human) to exploit forest lands than Logger X.
Pre-treatment	Both case studies treated the residual biomass previously by chipping or baling it.	Logger X does not have the equipment necessary to chip or bale. Therefore, it must rent it from third parties. Logger Y has all the required equipment.
Storage	When the residual biomass is insufficient to be transported in full truckload (FLT), it is collected in bulk and transported to an open-air park.	Logger X has an open-air park in Figueira da Foz. Logger Y has two open-air parks, one in Soure and the other in Monte Redondo.
Transportation	The transportation is mainly done directly to the customer. Loggers X and Y are responsible for transporting residues from the suppliers to the customers.	The transportation cost for Logger X is relatively low since its only customer is in the same municipality as most of its suppliers. Logger Y has a higher transportation cost due to its suppliers' geographic dispersion (all municipalities of Portugal).

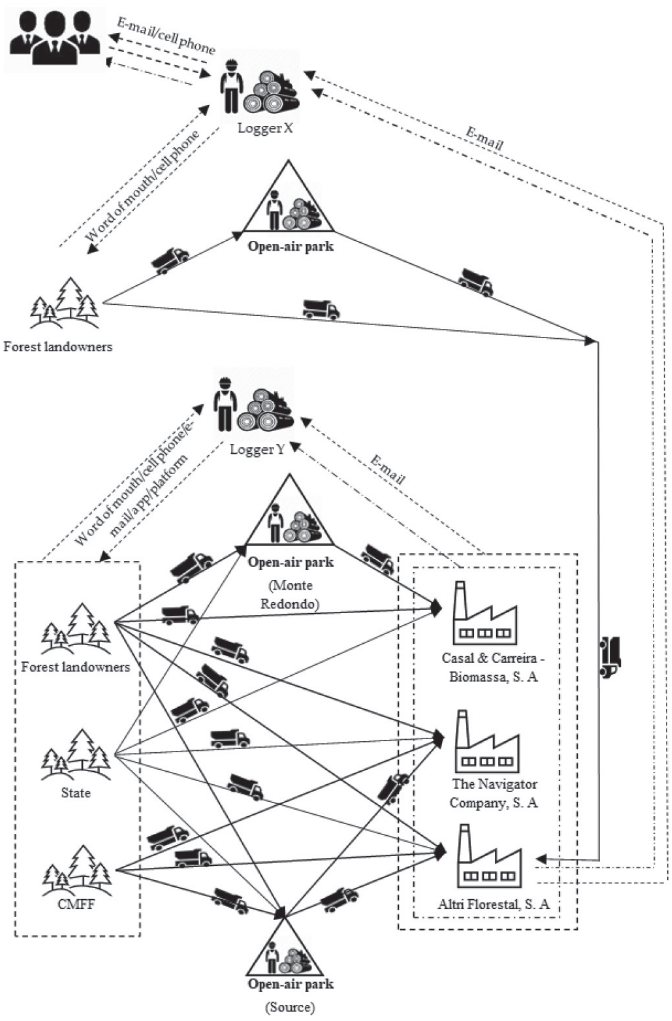


Figure 5. Residual forestry biomass SC mapping from case studies

flows can have a negative impact on the overall efficiency and profitability of the valorization process [9].

One notable disparity observed in the case studies is the difference in transportation costs between the two logging companies. Logger Y incurs higher transportation expenses because its suppliers are scattered across various geographic zones, compared to Logger X, whose suppliers are concentrated in the same municipality as its customer. This cost disparity challenges the economic viability of biomass valorization, as higher transportation costs reduce profit margins and competitiveness [3, 36]. To address this issue, it is crucial to explore strategies that optimize transportation efficiency and reduce costs [36]. One potential approach is consolidating biomass collection and delivery routes, minimizing empty trips and maximizing transportation capacity utilization. This can be achieved through collaborative initiatives among suppliers, loggers, and customers to synchronize collection schedules and coordinate logistics. Additionally, leveraging technology solutions such as route optimization software and real-time tracking systems can enhance operational efficiency and minimize transportation costs [5,36]. These measures improve the profitability of biomass valorization and contribute to environmental sustainability by reducing fuel consumption and greenhouse gas emissions associated with transportation.

The case studies also highlight a significant concern regarding the limited negotiation power of farmers and forest owners in determining residual forestry biomass prices. Their lack of knowledge about the value of wood residues and the absence of a reference pricing mechanism exposes them to unfair trade practices and exploitation by logging companies. This undermines their economic sustainability and hampers the overall development of the biomass valorization sector. To enhance the bargaining power of farmers and forest owners, it is crucial to empower them with knowledge and resources. This can be achieved through awareness programs, training initiatives, and access to information on market trends, pricing models, and alternative valorization opportunities [5, 56, 57]. Collaborative platforms and networks can also be established to facilitate collective bargaining and information sharing among stakeholders [3, 5, 25, 58]. Moreover, engaging relevant industry associations, regulatory bodies, and policymakers can help advocate for fair pricing practices and create a supportive policy environment that protects the interests of farmers and forest owners [4, 13, 57].

By providing insights about the available valorization resources, this study's findings can help manufacturers make informed decisions about production planning and resource allocation. Additionally, addressing transportation cost disparities by optimizing transportation efficiency and reducing costs can improve the profitability of biomass valorization. Enhancing the bargaining power of farmers and forest owners through awareness programs, training initiatives, and access to information can also help create a supportive policy environment that protects their interests. These measures not only improve the economic sustainability of the biomass valorization sector but also contribute to environmental sustainability by reducing fuel consumption and greenhouse gas emissions associated with transportation.

6. Conclusion

The primary objective of this study is to suggest a map for the valorization of the residual forestry biomass supply chain in order not only to identify better and understand the material, financial, and informational flows but also to give important insight into the economic dimension of its valorization (costs) and challenges. This objective was successfully achieved by answering the research question, “How is a residual forestry biomass supply chain organized, as well as its material and information flows?” The proposal map provides a comprehensive overview of the relationships between different entities in the SC, enabling better visualization and identification of inefficiencies such as long transportation distances, lack of processing infrastructure, or limited demand for the final product. Once these issues have been identified, it is possible to develop strategies to address them and improve the overall efficiency and sustainability of the SC.

While this study provides valuable insights into the organization and potential for sustainability within the residual forestry biomass SC, it is important to consider its limitations. The findings are based on only two case studies from just one country which could give rise to some bias and a need for a more robust analysis. The case studies are only from Portugal, which could not reflect the reality of other countries. Also, more case studies should be explored and analyzed to give more information about the reality of this sector, allowing us to propose a map more robustly.

Future research could involve developing a platform or app that provides information about the value of woodlands to address the current lack of market price for residual forestry biomass. Additionally, integrating agricultural residues into renewable energy and bioproduct production could identify another type of SC for their valorization. To overcome this study's main limitations of this study, it should consider more case studies and other countries as research units.

Nevertheless, this study has provided valuable insights into the organization and potential for sustainability within the residual forestry biomass SC. However, its limitations should be taken into account when generalizing its findings.

Funding

This work was supported by the FCT—Fundação para a Ciência e a Tecnologia, I.P., through national funds and co-financed by the FEDER project “Sustainable Supply Chain Management Model for Residual Agro-forestry Biomass supported in an Web Platform” [grant number PCIF/GVB/0083/2019]. Also, the work was supported through the projects UIDB/05037/2020 (CeBER), UIDB/04058/2020 (GOVCOPP), UIDB/00319/2020 (Algoritmi), in addition to UIDB/00667/2020 and UIDP/00667/2020 (UNIDEMI).

References

[1] X. Zhang, H. Li, J. T. Harvey, A. A. Butt, M. Jia, and J. Liu, “A review of converting woody biomass waste into useful and eco-friendly road materials,” Transportation Safety and Environment, vol. 4, no. 1, 2022, doi:10.1093/tse/tdab031.

[2] M. Casau, M. F. Dias, J. C. Matias, and L. J. Nunes, “Residual biomass: A comprehensive review on the importance, uses and potential in a circular bioeconomy approach,” Resources, vol. 11, no. 4, p. 35, 2022, doi:10.3390/resources11040035.

[3] T. Karras, A. Brosowski, and D. Thrän, “A review on supply costs and prices of residual biomass in techno-economic models for Europe,” Sustainability, vol. 14, no. 12, p. 7473, 2022, doi:10.3390/su14127473.

[4] R. S. Schillo, D. A. Isabelle, and A. Shakiba, “Linking advanced biofuels policies with stakeholder interests: A method building on quality function deployment,” Energy Policy, vol. 100, pp. 126–137, 2017, doi:10.1016/j.enpol.2016.09.056.

[5] N. Zandi. Atashbar, N. Labadie, and C. Prins, “Modeling and optimization of biomass supply chains: A review and a critical look,” IFAC-PapersOnLine, vol. 49, no. 12, pp. 604–615, 2016, doi:10.1016/j.ifacol.2016.07.742.

[6] F. L. Braghiroli and L. Passarini, “Valorization of biomass residues from forest operations and wood manufacturing presents a wide range of sustainable and innovative possibilities,” Current Forestry Reports, vol. 6, no. 2, pp. 172–183, 2020, doi:10.1007/s40725-020-00112-9.

[7] G. Maraver, A. F. Ramos Ridao, D. P. Ruiz, and M. Zamorano, “Quality of pellets from olive grove residual biomass,” Renewable Energy and Power Quality Journal, vol. 1, no. 08, pp. 751–756, 2010, doi:10.24084/repqj08.463.

[8] H. Carvalho, V. C. Machado, and J. G. Tavares, “A mapping framework for assessing supply chain resilience,” International Journal of Logistics Systems and Management, vol. 12, no. 3, p. 354, 2012, doi:10.1504/ijlsm.2012.047606.

[9] B. Mansoornejad, E. N. Pistikopoulos, and P. R. Stuart, “Scenario-based strategic supply chain design and analysis for the forest biorefinery using an Operational Supply Chain Model,” International Journal of Production Economics, vol. 144, no. 2, pp. 618–634, 2013, doi:10.1016/j.ijpe.2013.04.029.

[10] F. T. Couto, F. L. Santos, C. Campos, N. Andrade, C. Purificação, and R. Salgado, “Is Portugal starting to burn all year long? the transboundary fire in January 2022,” Atmosphere, vol. 13, no. 10, p. 1677, 2022, doi:10.3390/atmos13101677.

[11] S. Chopra and P. Meindl, Supply Chain Management: Strategy, Planning, And Operation, 7th ed. One Street Lake, New Jersey: Pearson, 2021.

[12] D. Šafařík, P. Hlaváčková, and J. Michal, “Potential of forest biomass resources for renewable energy production in the Czech Republic,” Energies, vol. 15, no. 1, p. 47, 2021, doi:10.3390/en15010047.

[13] G. Berndes, B. Abt, A. Asikainen, A. Cowie, V. Dale, G. Egnell, M. Lindner, L. Marelli, D. Paré, K. Pingoud, and S. Yeh, “Forest biomass, carbon neutrality and climate change mitigation. From Science to Policy, “ European Forest Institute, 2016, doi:10.36333/fs03.

[14] W. Deng, Y. Feng, J. Fu, H. Guo, Y. Guo, B. Han, Z. Jiang, L. Kong, C. Li, H. Liu, P. T. T. Nguyen, P. Ren, F. Wang, S. Wang, Y. Wang, Y. Wang, S. S. Wong, K. Yan, N. Yan, X. Yang, Y. Zhang, Z. Zhang, X. Zeng, and H. Zhou, “Catalytic conversion of lignocellulosic biomass into chemicals and fuels,” Green Energy & Environment, vol. 8, no. 1, pp. 10–114, 2023, doi:10.1016/j.gee.2022.07.003.

[15] M. Dunky and A. Pizzi, “Chapter 23 - Wood adhesives,” in Adhesion Science and Engineering, D. A. Dillard, A. V Pocius, and M. Chaudhury, Eds., Amsterdam: Elsevier Science B.V., 2002, pp. 1039–1103. doi: 10.1016/B978-044451140-9/50023-8.

[16] V.-H. Antolín-Cerón, F.-J. González-López, P. D. Astudillo-Sánchez, K.-A. Barrera-Rivera, and A. Martínez-Richa, “High-performance polyurethane nanocomposite membranes containing cellulose nanocrystals for protein separation,” Polymers, vol. 14, no. 4, p. 831, 2022, doi:10.3390/polym14040831.

[17] L. Hamelin, M. Borzęcka, M. Kozak, and R. Pudełko, “A spatial approach to bioeconomy: Quantifying the residual biomass potential in the EU-27,” Renewable and Sustainable Energy Reviews, vol. 100, pp. 127–142, 2019, doi:10.1016/j.rser.2018.10.017.

[18] Y. Torreiro, L. Pérez, G. Piñeiro, F. Pedras, and A. Rodríguez-Abalde, “The role of energy valuation of agroforestry biomass on the circular economy,” Energies, vol. 13, no. 10, p. 2516, 2020, doi:10.3390/en13102516.

[19] M. Costa, D. Piazzullo, D. Di Battista, and A. De Vita, “Sustainability assessment of the whole biomass-to-energy chain of a combined heat and power plant based on biomass gasification: Biomass Supply Chain Management and life cycle assessment,” Journal of Environmental Management, vol. 317, p. 115434, 2022, doi:10.1016/j.jenvman.2022.115434.

[20] S. Wu, S. Zhang, C. Wang, C. Mu, and X. Huang, “High-strength charcoal briquette preparation from hydrothermal pretreated biomass wastes,” Fuel Processing Technology, vol. 171, pp. 293–300, 2018, doi:10.1016/j.fuproc.2017.11.025.

[21] J. Karthäuser, V. Biziks, C. Mai, and H. Militz, “Lignin and lignin-derived compounds for wood applications—a review,” Molecules, vol. 26, no. 9, p. 2533, 2021, doi:10.3390/molecules26092533.

[22] Z. Chen and C. Wan, “Biological valorization strategies for converting lignin into fuels and chemicals,” Renewable and Sustainable Energy Reviews, vol. 73, pp. 610–621, 2017, doi:10.1016/j.rser.2017.01.166.

[23] J. Becker and C. Wittmann, “A field of dreams: Lignin valorization into chemicals, materials, fuels, and health-care products,” Biotechnology Advances, vol. 37, no. 6, p. 107360, 2019, doi:10.1016/j.biotechadv.2019.02.016.

[24] M. Dashtpeyma and R. Ghodsi, “Forest biomass and Bioenergy Supply Chain Resilience: A systematic literature review on the barriers and Enablers,” Sustainability, vol. 13, no. 12, p. 6964, 2021, doi:10.3390/su13126964.

[25] H. Stadtler, Supply Chain Management and advanced planning: Concepts, models, software and case studies, 4th ed. Berlin, Germany: Springer, 2008.

[26] P. L. King and J. S. King, Value stream mapping for the process industries: Creating a roadmap for Lean Transformation, 1st ed. New York, USA: CRC Press, 2017.

[27] L. J. R. Nunes, M. Casau, M. F. Dias, J. C. O. Matias, and L. C. Teixeira, “Agroforest woody residual biomass-to-energy supply chain analysis: Feasible and sustainable renewable resource exploitation for an alternative to fossil fuels,” Results in Engineering, vol. 17, p. 101010, 2023. doi:10.1016/j.rineng.2023.101010.

[28] C. Cambero, T. Sowlati, M. Marinescu, and D. Röser, “Strategic optimization of forest residues to bioenergy and Biofuel Supply Chain,” International Journal of Energy Research, vol. 39, no. 4, pp. 439–452, 2014. doi:10.1002/er.3233.

[29] H. Woo, M. Acuna, S. Cho, and J. Park, “Assessment techniques in forest biomass along the timber supply chain,” Forests, vol. 10, no. 11, p. 1018, 2019. doi:10.3390/f10111018.

[30] B. Rijal, S. H. Gautam, and L. LeBel, “The impact of forest disturbances on residual biomass supply: A long-term forest level analysis,” Journal of Cleaner Production, vol. 248, p. 119278, 2020. doi:10.1016/j.jclepro.2019.119278.

[31] A. J. A. Urquiaga, N. S. Cossío, J. A. Acevedo-Suárez, and A. J. Urquiaga-Rodríguez, “A model with a collaborative approach for the operational management of the supply chain,” International Journal of Industrial Engineering and Management, vol. 12, no. 1, pp. 49-62, 2021, doi: 10.24867/IJIEM-2021-1-276.

[32] A. Jankovic-Zugic, N. Medic, M. Pavlovic, T. Todorovic, and S. Rakic, “Servitization 4.0 as a trigger for sustainable business: Evidence from Automotive Digital Supply Chain,” Sustainability, vol. 15, no. 3, p. 2217, 2023. doi:10.3390/su15032217.

[33] O. Anichkina et al., “A novel mathematical model to design an agile supply chain for perishable products,” International Journal of Industrial Engineering and

Management, vol. 13, no. 2, pp. 88–98, 2022. doi: 10.24867/IJIEM-2022-2-303.

[34] A. Kumar, S. Adamopoulos, D. Jones, and S. O. Amiandamhen, "Forest biomass availability and utilization potential in Sweden: A Review," Waste and Biomass Valorization, vol. 12, no. 1, pp. 65–80, 2020, doi: 10.1007/s12649-020-00947-0.

[35] A. A. Rentizelas, "Biomass storage," in Biomass Supply Chains for Bioenergy and Biorefining, J. B. Holm-Nielsen and E. A. Ehimen, Eds., Woodhead Publishing, 2016, pp. 127–146. doi: 10.1016/B978-1-78242-366-9.00006-X.

[36] M. S. Roni, S. D. Eksioglu, E. Searcy, and J. J. Jacobson, "Estimating the variable cost for high-volume and long-haul transportation of densified biomass and biofuel," Transportation Research Part D: Transport and Environment, vol. 29, pp. 40–55, 2014, doi: 10.1016/j.trd.2014.04.003.

[37] A. Ilari, E. Foppa Pedretti, C. De Francesco, and D. Duca, "Pellet production from residual biomass of greenery maintenance in a small-scale company to improve sustainability," Resources, vol. 10, no. 12, p. 122, 2021, doi: 10.3390/resources10120122.

[38] L. R. A. Ferreira, R. B. Otto, F. P. Silva, S. N. M. De Souza, S. S. De Souza, and O. H. Ando Junior, "Review of the energy potential of the residual biomass for the distributed generation in Brazil," Renewable and Sustainable Energy Reviews, vol. 94, pp. 440–455, 2018, doi: 10.1016/j.rser.2018.06.034.

[39] K. Rimienė and D. Grundey, "Logistics Centre concept through evolution and definition," Engineering Economics, vol. 54, no. 4, 2007.

[40] N. Shabani, S. Akhtari, and T. Sowlati, "Value chain optimization of forest biomass for Bioenergy Production: A Review," Renewable and Sustainable Energy Reviews, vol. 23, pp. 299–311, 2013, doi: 10.1016/j.rser.2013.03.005.

[41] B. L. MacCarthy, W. A. H. Ahmed, and G. Demirel, "Mapping the supply chain: Why, what and how?," International Journal of Production Economics, vol. 250, p. 108688, 2022, doi:10.1016/j.ijpe.2022.108688.

[42] J. T. Gardner and M. C. Cooper, "Strategic Supply Chain Mapping Approaches," Journal of Business Logistics, vol. 24, no. 2, pp. 37–64, 2003, doi: 10.1002/j.2158-1592.2003.tb00045.x.

[43] M. S. Mubarik, N. Naghavi, M. Mubarik, S. Kusi-Sarpong, S. A. Khan, S. I. Zaman, and S. H. Kazmi, "Resilience and cleaner production in industry 4.0: Role of supply chain mapping and visibility," Journal of Cleaner Production, vol. 292, p. 126058, 2021, doi: 10.1016/j.jclepro.2021.126058.

[44] S. Y. Cha, "The art of cyber security in the age of the digital supply chain: detecting and defending against vulnerabilities in your supply chain," in The Digital Supply Chain, B. L. MacCarthy and D. Ivanov, Eds., Elsevier, 2022, pp. 215–233. doi: https://doi.org/10.1016/B978-0-323-91614-1.00013-7.

[45] Ghadge, M. Er Kara, H. Moradlou, and M. Goswami, "The impact of industry 4.0 implementation on supply chains," Journal of Manufacturing Technology Management, vol. 31, no. 4, pp. 669–686, 2020, doi: 10.1108/JMTM-10-2019-0368.

[46] M. Theodore Farris, "Solutions to strategic supply chain mapping issues," International Journal of Physical Distribution and Logistics Management, vol. 40, no. 3, pp. 164–180, 2010, doi:10.1108/09600031011035074.

[47] P. Childerhouse and D. R. Towill, "Simplified material flow holds the key to supply chain integration," Omega, vol. 31, no. 1, pp. 17–27, 2003, doi:10.1016/s0305-0483(02)00062-2.

[48] D. I. Miyake, A. S. Torres Junior, and C. Favaro, "Supply chain mapping initiatives in the Brazilian automotive industry: challenges and opportunities," Journal of Operations and Supply Chain Management, vol. 3, no. 1, p. 78, 2010, doi: 10.12660/joscmv3n1p78-97.

[49] P. S. Thirumurugan, "Social Network Analysis of Team Communication And Supply chain Interactions in Manufacturing Industry," M.S. thesis, Pennslyvania State University, Pennslyvania, USA, 2018.

[50] R. K. Yin, Case study research and applications: Design and methods. Los Angeles, CA, USA: SAGE, 2018.

[51] S. Crowe, K. Cresswell, A. Robertson, G. Huby, A. Avery, and A. Sheikh, "The case study approach," BMC Medical Research Methodology, vol. 11, no. 1, 2011, doi: 10.1186/1471-2288-11-100.

[52] A. Priya, "Case study methodology of qualitative research: Key attributes and navigating the conundrums in its Application," Sociological Bulletin, vol. 70, no. 1, pp. 94–110, 2020. doi:10.1177/0038022920970318.

[53] C. Makri and A. Neely, "Grounded theory: A guide for exploratory studies in management research," International Journal of Qualitative Methods, vol. 20, p. 160940692110136, 2021. doi:10.1177/16094069211013654.

[54] M. Rodrigues, À. Cunill Camprubí, R. Balaguer-Romano, J. Ruffault, P. M. Fernandes, and V. R. de Dios, "Drivers and implications of the extreme 2022 wildfire season in Southwest Europe," 2022, doi:10.1101/2022.09.29.510113.

[55] S. Khan and R. VanWynsberghe, "Cultivating the Under-Mined: Cross-Case Analysis as Knowledge Mobilization", FQS, vol. 9, no. 1, Jan. 2008. doi:10.17169/fqs-9.1.334.

[56] P. Rijal, H. Carvalho, J. Matias, S. Garrido, and C. Pimentel, "Towards a conceptual framework for agroforestry residual biomass sustainable business models," Quality Innovation and Sustainability, pp. 211–221, 2023. doi:10.1007/978-3-031-12914-8_17.

[57] L. Yu et al., "Policy analysis of biomass recycling supply chain considering carbon and pollution emission reduction—taking China's straw subsidy policy for example," Systems, vol. 11, no. 7, p. 343, 2023. doi:10.3390/systems11070343.

[58] B. C. Chidozie, A. L. Ramos, J. V. Ferreira, and L. P. Ferreira, "Residual agroforestry biomass supply chain simulation insights and directions: A systematic literature review," Sustainability, vol. 15, no. 13, p. 9992, 2023. doi:10.3390/su15139992.