# OPTIMISATION OF THE REVERSED SUPPLY CHAIN OF WOOD BIOMASS IN THE PERSPECTIVE OF ITS EMISSIVITY - CASE STUDY

**Damian Dubisz**
Łukasiewicz Research Network – Poznań Institute of Technology, Poznań, Poland
Poznan University of Technology, Faculty of Engineering Management, Poznan, Poland
E-mail: damian.dubisz@pit.lukasiewicz.gov.pl

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***Abstract***

Evaluating the carbon footprint level is critical when deciding on the shape of supply chains. The efficiency index of logistic processes referring directly to their emissivity may also indicate their technological and organisational advancement level. Such an approach is present in Green Supply Chains (GrSC) and Sustainable Supply Chains (SSC). Elements of these approaches can be applied to reversed supply chains of wood biomass. In this study, the differences in carbon footprint emissions for different shape variants of reversed supply chains of wood biomass are analysed. Based on the conducted research, a set of recommendations and identified dependencies between the elements of the process and its effectiveness were developed. The case study part of this paper was devoted to calculations of the carbon footprint related to the logistic service of wood biomass. Based on calculations of the carbon dioxide equivalent (kgCO2e) level, an attempt was made to indicate the most favourable setup of the reversed supply chain of wood biomass.
The research results may be considered when modelling reversed supply chains of wood biomass.

**Keywords:** carbon footprint, reverse logistics, carbon accounting, wood biomass, efficiency

## 1. INTRODUCTION

The potential of increasing transport processes' efficiency thru their decarbonization is a burning issue (Chaabane et al., 2012; Chen et al., 2017; Farm Europe, 2019; Herrador et al., 2022; ITF, 2018a, 2018b; Ku et al., 2021). The legal framework within Europe enforces the motivation to reduce transportation carbon footprint (European Commission, 2020). Simultaneously, vital out of the EU's international environmental policies are present (UN, 2015; UNFCCC, 1997). Carbon footprint mitigation solutions that lead signatories to international climate protection agreements to view emissions as a finite resource. Hence its proper evaluation and management have to be introduced within sustainable supply chains. According to this approach, emissions trading schemes or management methodologies have been proposed – In Europe: French Bilan Carbone, EU Emission Trading Scheme, Dutch Energy Covenant, and The Carbon Trust Standard. In North America, US EPA GHG Rule, US GHG Protocol Public Sector Standard, US EPA Climate Leaders Inventory Guidance, US Regional Greenhouse Gas Initiative, and US Securities and Exchange Commission Guidance (Dubisz et al., 2021). However, regardless of the chosen method, each supply chain participant involved in the carbon footprint evaluation is obliged to measure and report its carbon footprint properly. A practical approach for seeking an opportunity to minimize the anthropological impact on the environment is the 3R concept (Golinska-Dawson, 2020) The Circular Economy (CE) aims to maximize the use of once-processed resources. The processing of wood biomass of various origins can be an executive tool of this concept (Danish et al., 2018). Reusing once-obtained resources supports the reduction of the anthropological impact on the environment (Golinska-Dawson et al., 2020).

Additional support for this concept and verification of potential efficiency increase can be provided by assessing the environmental performance of transport processes from the perspective of the carbon footprint level expressed as kgCO2e (Acquaye et al., 2014).

## 2. LITERATURE REVIEW

The need for improvement in the efficiency of wood biomass supply chains has been the subject of attention in the available literature. Numerous supply chain control parameters have been identified as having a direct impact on supply chain efficiency. An important approach highlights the particular importance of solving supply chain organization problems in terms of distance - Maximum Allowable Travel Distance (MATD). The use of tools such as multiple linear regression (MLR) helps to identify cost effectiveness correlations (Lam et al., 2023). The significant dynamics of change in the handling of wood biomass from different origins indicate the need for the implementation of mechanisms that allow for spatial and temporal variability in supply chains handling wood biomass. Inadequate modelling of supply chains may lead to an underestimation of the actual costs of biomass handling. This highlights the importance of optimizing reverse wood biomass supply chains (Roni et al., 2023). The role of selected capacity parameters of the supply chain participants and their location, which have an influence on the change of the cost efficiency level, is recognised. The verification of the efficiency can be carried out by modelling a simulation under different scenarios. Both raw material flow efficiency and level of financial benefits achieved can be assessed (Kim et al., 2011). The growing role of forest wood biomass supports the reduction of anthropogenic environmental impacts. There is a direct impact on economic, social and environmental aspects of the long-term use of wood biomass. The combination of selected areas, such as economic efficiency and environmental performance, is the focus of efforts to optimise processes for handling wood biomass flows. The proper modelling and optimisation of reverse wood biomass supply chain processes is supported by environmental indicators oriented towards the measurement of greenhouse gas emissions (Cambero et al., 2014).

A literature review was conducted to identify factors influencing the efficiency of reverse supply chains of wood biomass. In the first research step, an attempt was made to identify factors influencing the carbon performance of the transport fleet. It was recognized that the degree of filling of vehicles(Korpinen et al., 2019), vehicle age (Dubisz et al., 2022), total weight (Brown, 2021) allowed and fuel type (McDowall, 2014; Parra et al., 2019) are the main factors determining the carbon performance of a heterogeneous fleet (Dubisz et al., 2022). Another crucial factor is the driver's style of driving(Zamboni et al., 2015). An urban transport study showed that each bus driver following the same route using the same type of vehicle has a unique carbon footprint(Zarkadoula et al., 2007). Route planning itself and the routing of points along the route are also important (Sar et al., 2023). For this purpose, advanced route modelling algorithms can be used, but such a universal tool that applies to the different types of routes might be challenging to implement (Lee et al., 2016). The effectiveness of route modelling tools in the case of linehaul transports between fixed points is lowered (Melo et al., 2006). The available literature also verifies the influence of the degree of filling of vehicles. It was pointed out that many studies indicate the importance of this parameter while improving the efficiency of transport processes (Brown, 2021; Kogler et al., 2020; Korpinen et al., 2019; Wong et al., 2018). Therefore, it was determined to verify the types of transport units present within reversed supply chains of wood biomass. The loading unit types identified for handling wood biomass were mainly big bags, pallets, and cage containers (Do et al., 2022; Hogland et al., 2018; Keefe et al., 2014). According to the identified packaging types, an idea for each packaging type environmental efficiency evaluation in the case study part was extended. Hence efficiency assessment in alternative transport of wood biomass scenarios was proposed. Simultaneously impact of increasing the volume of wood biomass within the supply chain on its efficiency was verified (Kogler et al., 2018). Another study verified the mutual dependencies between control parameters that affect the change in efficiency while handling various materials within the supply chain (Ghosh et al., 2022). Other studies indicate the need to properly correlate the demand-supply model in order to guarantee its proper effectiveness. This approach can also be applied to the handling of wood biomass within reversed supply chains (Al-Babtain, 2010). Simultaneously it was noticed that the efficiency of transport processes within the reverse supply chains in terms of usage of alternative packaging types needs to be analysed. Identified research gap was a motivation for conducting further research outlined within a case study research stage. In o order to assess changes in efficiency, the case study section of the study further simulated the efficiency of handling woody biomass in reverse supply chains.

## 3. RESEARCH METHODOLOGY

A literature study was carried out in the field of identifying control parameters affecting the effectiveness of reverse supply chains. At the same time, the available types of bulk packaging suitable for use in forming loading units of post-production wood biomass were verified. The simulation was carried out for the identified types of packaging, and the results were presented in scenarios. The proposed approach made it possible to compare the results and indicate the best solution. Based on the conducted research, answers to the research studies were formulated. According to the scope of the research's importance, it was decided to conduct research into improving the environmental efficiency of transport processes within the reverse supply chains of wood biomass.

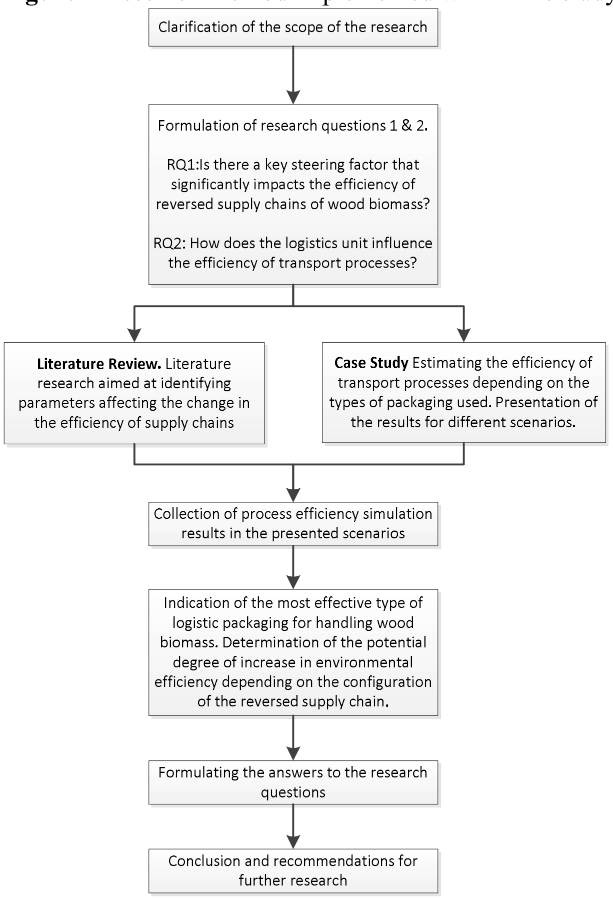
The following research questions were outlined:

Research Question 1: Is there a key steering factor that significantly impacts the efficiency of reversed supply chains of wood biomass?

Research Question 2: How does the logistics unit influence the efficiency of transport processes?

The conducted study is an attempt to answer the research questions proposed. The logic of the research is shown in **Pogreška! Izvor reference nije pronađen.**.

**Figure 1** Research method implemented within this study

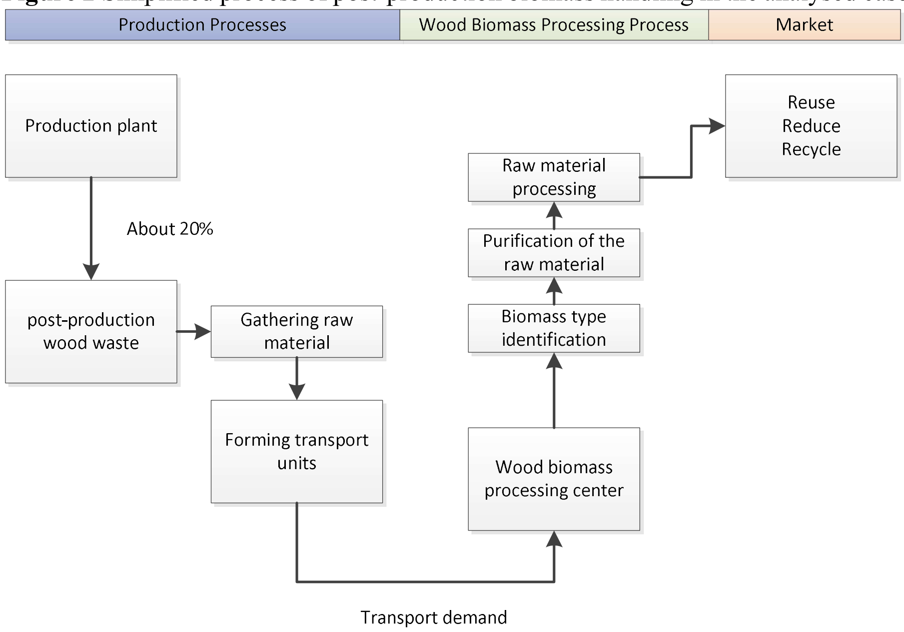



Source: own elaboration

## 3. CASE STUDY

The case study research was conducted using basic data of a manufacturing company in the furniture industry. The information on the company's internal flows included in the data allowed to estimate the overall level of post-production waste. Anonymized basic data of a company involved in the production of wooden furniture was used in the simulation. For this purpose actual production data of 25379 indexes was used for further calculations within scenarios. Gathered data describes production volumes for 2021. It has been observed that during the production process about 20% of production waste is turned into wood biomass. Based on the indicators developed, the level of production waste was estimated by product group. The processed waste feeds into the reversed supply chain of wood biomass. Once the waste material is obtained and loaded onto the trucks is transferred to proper processing centres. The general functional scope of the reverse supply chain is presented in the **Pogreška! Izvor reference nije pronađen.** below.

**Figure 2** Simplified process of post-production biomass handling in the analysed case




Source: own elaboration

The reverse supply chain has identified three main areas: Production Processes, Wood Biomass Processing Processes, and Market. The primary participant in the supply chain is the production plant which generates post-production wood biomass. It has been outlined in **Pogreška! Izvor reference nije pronađen.** that about 20% of the volume is post-production waste. This is a very high waste indicator that forces proper raw material management. The formation of logistic units precedes the grouping of biomass within the production plan premises. However, there are no standardized transport units in the current logistics model. Therefore, the shape of the formed logistics units is difficult to assess and classify. This results in the allocation of only 40-ton vehicles with a capacity of up to 33 pallets. The wood biomass processing centre is another essential participant within the reverse supply chain of wood biomass. The distance between the participants in the supply chain is 134 km; therefore, sending additional transports will significantly increase the emissivity of the reversed supply chain of wood biomass. The main tasks of the biomass processing centre include identifying the type of biomass, sorting, separating undesirable residues, purifying the raw material, and further processing depending on its further destination and utility purposes. The market is the last area within the supply chain, which determines the method of processing wood biomass waste. The entire functional course of the supply chain is consistent with the 3R concept (reuse, reduce, recycle) and is in line with the assumptions of the circular economy (Krstić et al., 2022; Stahel, 2016).

Based on the packaging types dedicated to wood biomass handling indicated during the literature research, the effect of standardised packaging types on the change in the emissivity level of reversed supply chains of wood biomass was verified. For this purpose, the six packaging types indicated in Table 1 were implemented in simulation scenarios. For each of the defined types of packaging, basic parameters have been indicated. Including width, depth and height. During the verification of types of packaging, the focus was put on weight, volume and capacity. These parameters directly affect the filling level of the vehicles and the environmental performance of the entire reversed wood biomass supply chain presented in further scenarios.

**Table 1** Packaging types implemented for wood biomass handling in alternative distribution scenarios.

| | Capacity | | Dimensions & Specification | | | | |
|---|---|---|---|---|---|---|---|
| Packaging type | Maximum weight [kg] | Maximum cbm [litres] | Packaging weight [kg] | Packaging cbm [m3] | width [cm] | depth [cm] | height [cm] |
| Big Bag A | 1 000,00 | 480,00 | 30,63 | 0,48 | 1,11 | 0,71 | 0,61 |
| Big Bag B | 1 000,00 | 250,00 | 14,38 | 0,26 | 0,74 | 0,54 | 0,64 |
| Big Bag C | 1 000,00 | 820,00 | 41,90 | 0,83 | 1,11 | 0,91 | 0,82 |
| Cage Container A | 1 000,00 | 960,00 | 26,20 | 0,96 | 1,20 | 0,80 | 1,00 |
| Cage Container B | 1 000,00 | 760,00 | 24,20 | 0,77 | 1,20 | 0,80 | 0,80 |
| Cage Container C folding window | 1 000,00 | 1 152,00 | 32,90 | 1,15 | 1,20 | 0,80 | 1,20 |

Source: own elaboration

The efficiency of the logistic units implemented to handle the raw material, indicated in Table 1, was demonstrated through further simulation of alternative handling methods. Six scenarios were created and the result of each scenario was compared with the current model. In this way, a number of outcome parameters were demonstrated on the basis of which the level of efficiency was verified. The level of savings resulting from a reduction in the number of means of transport, the number of kilometres was indicated on this basis. It also showed a number of control parameters that were modelled for simulation in alternative operating scenarios. Means of transport characteristic is presented in **Pogreška! Izvor reference nije pronađen.**.

**Table 2** Packaging types implemented for wood biomass handling in alternative distribution scenarios.

| Truck type | 40 tonns lorry |
|---|---|
| Max. payload [kg] | 25 000 |
| Max. volume [m3] | 91 |
| kgCO2/km | 0,633 |
| Linehaul distance between Production Plant and Wood Biomass processing location [km] | 134 |

Source: own elaboration

The characteristics of the logistic units implemented to handle the post-production wood biomass are indicated in Table 1. Each solution's efficiency is demonstrated in the further simulation of alternative logistics unit types. In order to conduct a valid comparison of efficiency between six logistics units, four scenarios were created. The result of each scenario was compared according to its emissivity level expressed in kgCO2e units. Apart from the number of trucks engaged with transportation tasks, the overall emissivity level was calculated and shown in **Pogreška! Izvor reference nije pronađen.**.

Based on the conducted estimation, the emissivity level of each alternative scenario was evaluated. The methodology used for the evaluation was to measure the carbon footprint according to the GHG Protocol and the ISO 14064 standard (Crippa et al., 2021). To calculate the emissivity within each scenario, the available sets of emission factors were used as a dedicated data source. For this purpose, the emission sets published by UK DEFRA were used, mainly due to reliable information on the kgCO2e emissions factors of the different modes of transport, taking into account their GVM and the degree of filling of the cargo space. The result of the simulation is presented in **Pogreška! Izvor reference nije pronađen.**.

**Table 3** Emission efficiency evaluation for each packaging type dedicated to wood biomass handling.

| | Amount of packaging units per its type [Pcs] | | | | | |
|---|---|---|---|---|---|---|
| Month | Big Bag A | Big Bag B | Big Bag C | Cage Container A | Cage Container B | Cage Container C folding window |
| Jan | 1 442 | 2 870 | 907 | 714 | 864 | 570 |
| Feb | 763 | 1 520 | 480 | 378 | 458 | 302 |
| Mar | 697 | 1 387 | 439 | 345 | 418 | 276 |
| Apr | 1 753 | 3 490 | 1 103 | 868 | 1 051 | 693 |

| | | | | | | |
|---|---|---|---|---|---|---|
| May | 3 304 | 6 576 | 2 079 | 1 636 | 1 980 | 1 306 |
| Jun | 1 750 | 3 483 | 1 101 | 867 | 1 049 | 692 |
| Jul | 3 077 | 6 124 | 1 937 | 1 524 | 1 844 | 1 216 |
| Aug | 1 637 | 3 258 | 1 030 | 811 | 981 | 647 |
| Sep | 821 | 1 634 | 517 | 407 | 492 | 325 |
| Oct | 624 | 1 241 | 392 | 309 | 374 | 247 |
| Nov | 667 | 1 327 | 420 | 330 | 400 | 264 |
| Dec | 337 | 671 | 212 | 167 | 202 | 133 |

| | Amount of routes of 40 tonnes GVM trucks according to packaging unite type [Routes] | | | | | |
|---|---|---|---|---|---|---|
| Month | Big Bag A | Big Bag B | Big Bag C | Cage Container A | Cage Container B | Cage Container C folding window |
| Jan | 7,62 | 8,06 | 8,26 | 7,53 | 7,29 | 7,22 |
| Feb | 4,03 | 4,27 | 4,37 | 3,99 | 3,86 | 3,82 |
| Mar | 3,68 | 3,90 | 3,99 | 3,64 | 3,53 | 3,49 |
| Apr | 9,26 | 9,81 | 10,04 | 9,16 | 8,87 | 8,77 |
| May | 17,45 | 18,48 | 18,93 | 17,26 | 16,71 | 16,54 |
| Jun | 9,24 | 9,79 | 10,02 | 9,14 | 8,85 | 8,76 |
| Jul | 16,26 | 17,21 | 17,63 | 16,08 | 15,56 | 15,40 |
| Aug | 8,65 | 9,16 | 9,38 | 8,55 | 8,28 | 8,19 |
| Sep | 4,34 | 4,59 | 4,70 | 4,29 | 4,15 | 4,11 |
| Oct | 3,29 | 3,49 | 3,57 | 3,26 | 3,15 | 3,12 |
| Nov | 3,52 | 3,73 | 3,82 | 3,48 | 3,37 | 3,34 |
| Dec | 1,78 | 1,89 | 1,93 | 1,76 | 1,70 | 1,69 |

| | Carbon footprint of transportation processes - Production plant to Wood biomass processing center [kgCO2e] | | | | | |
|---|---|---|---|---|---|---|
| Month | Big Bag A | Big Bag B | Big Bag C | Cage Container A | Cage Container B | Cage Container C folding window |
| Jan | 646 | 684 | 700 | 638 | 618 | 612 |
| Feb | 342 | 362 | 371 | 338 | 327 | 324 |
| Mar | 312 | 330 | 338 | 309 | 299 | 296 |
| Apr | 785 | 831 | 851 | 776 | 752 | 744 |

| | | | | | | |
|---|---|---|---|---|---|---|
| May | 1 479 | 1 566 | 1 604 | 1 463 | 1 416 | 1 402 |
| Jun | 783 | 830 | 850 | 775 | 750 | 742 |
| Jul | 1 378 | 1 459 | 1 494 | 1 363 | 1 319 | 1 305 |
| Aug | 733 | 776 | 795 | 725 | 702 | 694 |
| Sep | 368 | 389 | 399 | 364 | 352 | 348 |
| Oct | 279 | 296 | 303 | 276 | 267 | 265 |
| Nov | 299 | 316 | 324 | 295 | 286 | 283 |
| Dec | 151 | 160 | 164 | 149 | 145 | 143 |
| Total carbon footprint [kgCO2e] | 7 554 | 7 999 | 8 191 | 7 471 | 7 233 | 7 157 |

Source: own elaboration

## 4. RESULTS

As a result of the simulations, it was shown that changing a logistics unit type for handling wood biomass may increase the overall efficiency of transportation processes. The obtained results showing the number of vehicles necessary for transport were deliberately left with the values after the decimal point. According to those results, it has been outlined that there are months in which 40-ton vehicles were not used effectively. It has been indicated that linehaul transports may be reduced between the production plant and the wood biomass processing centre due to the usage of alternative logistics unit packaging. The introduced change in the type of packaging contributed to minimizing the total number of kilometers travelled. Simultaneously the obtained result can be related to the supply chain's emissivity level using different types of transport packaging. The lowest emissivity level was obtained using Cage Container C with a folding window. The highest emission factor, expressed as kgCO2e, was obtained while using Big Bag type C. The difference in the demand for means of transport is as much as 12 trucks per year, depending on the packaging type. In response to research question 1, it was concluded that the key steering factor influencing the environmental performance of reverse wood biomass supply chains is the physical form of the transported volume. The aim to minimise its weight by changing its moisture content can positively influence the minimisation of the carbon footprint of transport processes as a result of the reduced need for transport resources. This approach is consistent with research conducted by Ungureanu et al. (2018). Regarding research question 2 it has been identified that the efficiency of the wood biomass supply chain is directly affected by the packaging type used. Transport demand can increase significantly if inappropriate types of packaging are applied. Conversely, choosing the right type of packaging can have a major impact on efficiency. This parameter should be considered as crucial while modelling reverse wood biomass supply chains.

## 5. CONCLUSION

Conducted research indicated the importance of logistic units in determining the efficiency level of transport processes of reversed supply chains of wood biomass. In order to improve the efficiency of transport processes and minimise their carbon footprint, the correct type of logistics units needs to be matched to the exact type of wood biomass. The identified potential increase in efficiency can translate into a significant reduction in logistics organisation costs. Thus it is essential to carry out further research into reducing the physical parameters of the raw material in terms of its volume and weight. Wood biomass may be reprocessed in order to reduce its moisture and volume. The conclusions of the literature study are confirmed by the simulation carried out using standardised types of packaging for the transport of wood biomass. Increasing transport efficiency is closely linked to the appropriate utilisation of transport unit loading space. The predictability of the physical form of the transported volume was increased by using standardised types of packaging. Through the use of several types of packaging, it is possible to select the appropriate loading unit for the quantity of wood biomass being transported. The method identified by Lam et al. (2023) for identifying the trade-off between cost and the level of efficiency achieved enables the efficiency of reverse wood biomass supply chains to be improved by introducing additional loading units, depending on the current needs of the supply chain. In line with the approach presented in the Cambero et al. (2014) stydy, the implementation of environmental indicators for the evaluation of the efficiency of the execution of distribution processes is considered to be feasible and can be used for the modelling and optimisation of supply chains. The idea of reducing cargo moisture content and changing its volume using hydraulic presses is also related to the approach outlined in other studies (Ungureanu et al., 2018).

The research has shown that using a standard of packaging dedicated to different types of wood biomass impacts the emissivity of reverse supply chain transport processes. It has been shown that the proper choice of suitable packaging is crucial to ensure standardisation of loading and unloading of the means of transport in production plants and wood biomass processing centres. Another critical factor that has to be analysed in further research is the time spent in the warehouse at loading and unloading trucks carrying logistics units of wood biomass. This could be an area of further research into the efficiency of handling woody biomass within reverse supply chains. However, the efficiency of warehouse processes can be assessed based on their energy consumption and related to the carbon footprint emission factors (kgCO2e).

The research also outlined that in periods of reduced demand for transport tasks, using vehicles with a lower capacity may be beneficial. The use of vehicles with lowered GVM will reduce the emissivity resulting from the implementation of transport routes and contribute to generating financial savings.

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