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Collaboration in the wood biomass supply chain for the circular economy: findings from empirical research

Abstract

Amid growing pressure to implement the principles of the circular economy, the wood biomass sector provides an important area in which it is possible to examine supply chain collaboration. This study aims to explore current collaboration between different actors in the management of wood residues, and to identify the challenges and opportunities for enhancing circularity. Focus group interviews were conducted with representatives from sawmills, wood manufacturers, logistics firms and energy companies. The analysis covered material flows, sorting practices, value recovery strategies and collaboration mechanisms. The findings reveal formal and informal cooperation practices, as well as key barriers such as transport costs, a lack of standardisation, and limited system integration. Participants identified potential solutions, including exchange platforms, shared logistics and fiscal incentives. The study makes recommendations to support the development of circular supply chains and argues that deeper cross-sector coordination, investment in enabling infrastructure, and improved information flow are critical to closing the loop in the wood biomass domain.

Keywords: wood biomass, supply chain collaboration, circular economy, reverse logistics, bioresource management
JEL Classification: L14, O13, Q53

Introduction

The transition towards a circular economy in the bioresource sector emphasizes maximizing the reuse and recycling of renewable materials while minimizing waste [Onukwulu et al., 2023]. Wood biomass is a prime example of a renewable resource with circular potential; it can be used to make products and its residuals (such as sawdust, offcuts, or post-consumer wood) can be recovered and used again instead of being thrown away [Kawa, Dujak, 2025]. Previous studies have noted that wood biomass largely originates from forestry operations, wood processing residues, and construction and municipal waste. It can be processed into new products or energy, providing an environmentally-friendly alternative to fossil fuels [Braghiroli, Passarini, 2020]. However, implementing circular principles in the wood biomass supply chain presents challenges [Kawa, 2024a]. Despite increasing environmental awareness in the industry, recovery rates for residual wood biomass remain relatively low [Thiffault et al., 2016]. While companies are investing in technological and logistics optimisations to reduce their environmental impact and costs, greater collaboration across the supply chain is needed to close the loop fully [Anaba et al., 2024]. Effective collaboration could transform what would otherwise be considered "waste" into feedstock for new value streams, thereby reducing overall waste and conserving primary forests [Nunes, 2025].

Numerous stakeholders within the wood industry generate or can utilize wood residues, including forestry enterprises, sawmills, wood-based panel manufacturers, bioenergy producers, farmers, and chemical companies [Makkonen, 2018]. It is crucial to ensure that these diverse actors communicate and coordinate to create a functioning circular supply chain [Kawa, 2023].

Beyond the confines of academic discourse, the dearth of collaboration within the wood biomass supply chain manifests as a palpable and pragmatic predicament for businesses and public stakeholders. In practice, many companies generating wood residues encounter difficulties in identifying reliable partners for their collection and reuse, leading to higher logistics costs, unstable outlets for by-products, and the underutilization or downgrading of potentially valuable biomass streams. This fragmentation has the effect of diminishing the economic viability of circular solutions, particularly for small and medium-sized firms, and it serves to weaken regional efforts to reduce waste and reliance on primary raw materials. Despite its practical importance, this coordination problem remains insufficiently explored at the operational level, creating a clear need for empirical research grounded in industry practice.

This study addresses the following research question: How do supply chain actors currently collaborate (or fail to collaborate) in managing wood biomass residues, and what are the major challenges and opportunities for improving circularity in this supply chain? By focusing on collaboration, the flows of residual biomass, as well as the organizational practices, agreements and information sharing needed to support them are given full consideration.

In order to explore these issues, qualitative research was conducted in the form of focus group interviews (FGIs) with practitioners in the wood biomass supply chain. Three FGIs were held with managers and specialists from various sectors of Poland's wood industry, including sawmill operators, wood product manufacturers, pellet producers, and logistics managers.

The remainder of this paper firstly provides a concise contextual overview of biomass in the circular economy, drawing upon the extant literature. Then, the FGI findings are presented alongside a discussion organized by the following key themes: supply chain structure and current collaborative practices, challenges in residual biomass utilization, and opportunities or missing practices that could enhance circularity. Finally, conclusions and implications for sustainable supply chain management and policy are drawn.

Literature review

Biomass is a cornerstone of the emerging circular bioeconomy because it is a renewable biological resource that can be regenerated and cycled through multiple uses [Casau, 2022; Sherwood, 2020]. In a circular economy model, biomass should be utilized in a series of steps: first for high-value products, then for reuse or recycling, and finally for energy recovery at the end of its life [Mair, Stern, 2017]. In particular, wood biomass has attracted interest due to its versatility [Usta, 2019]. It can be used to make solid products such as lumber, panels and furniture, or it can be processed into composites or chemicals. Its residues, such as sawdust, shavings, and bark, can be converted into energy sources such as pellets and briquettes, or into other materials such as fibreboard and mulch. Kawa and Pierański [2023] emphasize that residual wood biomass, ranging from forest slash to sawmill offcuts and even demolition wood, can be given a "second life" through various forms of recycling and reuse. This approach not only contributes to corporate cost savings but also aligns with environmental objectives.

From a supply chain perspective, managing wood biomass for circularity involves what is often termed a "reverse supply chain" or "closing the loop" [Dubisz, Kawa, 2023]. While traditional forward supply chains move timber from forests to processing and then finished products to consumers, the reverse chain collects wood residues from various sources, such as sawmill by-products, manufacturing scraps and post-consumer wood, and redirects them to new uses [Generowicz, Kowalski, 2020]. This reverse flow is inherently more complex because it involves heterogeneous materials, additional handling (collection, sorting, cleaning, etc.) and the matching of supply and demand across different industries (e.g. wood processing, energy, and agriculture) [Khan et al., 2024]. Previous studies on sustainable supply chain management indicate that collaboration is essential for enabling circular flows. Firms must share information, develop partnerships, and sometimes co-invest in technologies to utilize waste materials together [Alam et al., 2025]. In the wood sector, such collaborations could take the form of contracts between sawmills and panel board factories or pellet plants, take-back arrangements (e.g. window manufacturers retrieving old frames) or multi-sector networks linking municipalities, recyclers, and biomass users [Goh et al., 2013].

Despite growing scholarly interest in circular bioeconomy models, there is still a scarcity of empirical studies focusing on operational collaboration in wood biomass supply chains. Much of the existing literature concentrates on technological innovations or macro-level policy recommendations, while neglecting the everyday coordination challenges faced by companies on the ground [Kawa, 2024a; Prahinski, Kocabasoglu, 2006]. Furthermore, the unique characteristics of wood biomass, including its variability, bulkiness, and susceptibility to contamination, necessitate strategies that transcend generic circular economy frameworks [Jarre, 2020].

A recurring limitation of the literature is the assumption of seamless material flows and rational behaviour by actors in the supply chain, whereas in practice, these actors often operate under asymmetric information, diverging economic incentives and fragmented responsibilities. Effective collaboration is therefore not guaranteed, but rather a contested and negotiated process shaped by trust, the history of interactions, and local infrastructure [Parsa et al., 2021]. This study addresses these gaps by incorporating qualitative insights from practitioners, thereby grounding theoretical concepts in the operational realities of the sector.

A critical yet often overlooked barrier to circularity in biomass supply chains is the absence of standardized classification systems for wood residues. The literature acknowledges that the absence of uniform terminology and quality criteria impedes the efficient matching of biomass supply and demand across sectors [Mai-Moulin et al., 2019]. What one party considers a valuable by-product, another may consider waste, resulting in missed opportunities for reuse. Regulatory ambiguity further exacerbates this issue; in many jurisdictions, the legal status of certain residuals (waste versus product) is unclear, which discourages their circulation in secondary markets [Bastos et al., 2025 [. These institutional gaps contribute to market fragmentation and risk aversion, undermining long-term collaborative arrangements. Therefore, improving standardization and legal clarity is a foundational step in enabling more systemic forms of cooperation within circular wood biomass systems.

Methodology

The present research is grounded in three focus group interviews, which took place in 2022 and involved a total of 18 participants from across the wood biomass supply chain in Poland. Each focus group (FGI) comprised six participants with experience in various roles, such as sawmill managers, production engineers from wood product factories, pellet production specialists and logistics coordinators. Participants were recruited to ensure diversity of perspective across the supply chain (forestry/timber production, wood processing and residual biomass utilization). All participants had several years' experience in the industry and came from different regions of the country, reflecting both small and large-scale operations. The structure of the sample, categorized by gender, age, position, and industry focus, is delineated in [Kawa, Pierański, 2023].

FGIs were moderated by a facilitator using a semi-structured questionnaire. The discussions began with an introductory exercise in which participants wrote down their initial thoughts on the term "waste biomass" to familiarize themselves with the topic. The conversation then explored the following: (1) the types of wood biomass residues encountered, and how these are classified or grouped; (2) current practices for reusing or disposing of these residues, including collaboration with other firms; (3) actors involved in the reverse wood biomass supply chain (e.g. which companies or sectors are involved in collecting or using wood waste); (4) perceived challenges, barriers, opportunities, and improvements needed for better collaboration and the circular utilization of biomass. The focus groups lasted between 90 and 120 minutes each, were audio-recorded, and were transcribed verbatim for analysis. Participants were assured of confidentiality; thus, in our reporting, we do not use real names.

We conducted a thematic analysis using the transcripts. We coded the responses to identify key themes and patterns across the groups. The major themes that emerged were the classification of biomass residues; current reuse pathways and collaborations; supply chain dependencies and communication; logistics and economic challenges; technical and quality challenges; and opportunities or suggested improvements. The findings below integrate direct quotations from participants (translated from Polish to English) to illustrate each theme. The discussion of the findings considers not only common practices and issues, but also points of divergence or contradiction. This provides a nuanced picture of collaboration in the wood biomass supply chain.

Findings and discussion

Residual biomass flows and the supply chain structure

As mentioned above, in a conventional forward supply chain, wood flows from forestry operations to sawmills, which produce lumber, and then on to various wood product manufacturers, such as furniture makers, construction material producers and paper mills. Finally, it reaches end users. Throughout these stages, residual biomass is generated in the form of off-cuts at sawmills, sawdust from milling and sanding, wood shavings and bark, as well as end-of-life wood from used products. Participants in the focus groups described an interconnected network of actors handling these residuals, forming a reverse supply chain.

Several participants emphasized the interdependence of these supply chain actors. For instance, materials that leave one company as waste can become the raw material for another. A manager from a wood construction firm provided a concise example: "I sell my wood shavings and scraps to someone to produce OSB (oriented strand board), but then when carpenters build a house and need OSB, I have to buy it back, so my material comes back around." Another participant reflected more generally that "each of us collects something, sorts or stores something, then sells it and someone else makes something out of it – we are very dependent on each other." This circular interdependence means that communication and coordination are essential [Parsa et al., 2021]: a change or problem at one node (e.g. a pellet producer temporarily not buying sawdust) can quickly affect the others. Furthermore, roles can become indistinct, as noted by one individual, who observed that producers may engage in the acquisition of secondary materials, and waste handlers can transition into the provision of feedstock.

Focus group discussions confirmed that sawmills play a central role in the supply chain, acting as the main source of residual biomass. Sawmill by-products such as sawdust, wood chips, and bark were consistently mentioned as important inputs for other industries. Participants from sawmills described well-established practices for either utilizing these by-products internally or selling them externally. For instance, one sawmill deputy manager shared that "we don't deal with [processing] the sawdust and off-cuts; we hand them over to a company we cooperate with… we have a contract with a firm that handles all that biomass. We give them the leftovers from producing boards, floors, and beams." This indicates a formal collaboration in which a residue management company takes the wood waste in exchange for payment or services. In this example, the partner company specializes in biomass utilization: "They use it – bark goes for gardening and such, and any wood they can still recover and give a second life, they do". In other cases, sawmills or wood product firms sell their residues directly to specific end users. "We similarly sell to other companies, which use it either for manufacturing boards or for fuel, depending on the type of waste," explained another participant.

In addition, respondents identified other entities involved in the reverse supply chain of wood biomass residues. As one participant enumerated, the range of participants included "companies engaged in recycling, furniture manufacturers, construction material producers, chemical industry, paper industry… and also agricultural sector firms (tree bark can be used as animal bedding)." Another added "biofuel companies, pellet producers, charcoal makers" as obvious receivers of wood waste. Participants from waste management highlighted "landfills or waste collection centres" as key players: "even landfills deliver sorted wood material; and urban greenery maintenance firms that do tree trimming also send the wood they cut." This suggests that, in addition to the private sector, municipal waste systems and public landscaping departments also contribute to wood residue flows.

Based on focus group discussions, the structure of the wood biomass supply can be described as a set of interrelated actors. The following are included: primary wood processors generating residual biomass (e.g. sawmills, wood product manufacturers); specialized users of residual biomass (e.g. panel board factories, pellet producers, energy and chemical companies); intermediaries and service providers facilitating material flows (e.g. recycling firms, logistics service providers); and end-of-life and institutional actors contributing post-consumer wood (e.g. municipalities, waste collection systems).

Classification of residues and sorting practices

To facilitate the processes, companies must appropriately classify and sort their wood residues. Participants in the FGIs reported that they typically separate residues into categories such as wood type (hardwood vs. softwood), form/size (e.g. chips, sawdust, shavings, larger offcuts) and cleanliness/purity. This is partly because different end users demand different specifications. For example, pellet producers often prefer homogeneous, dry sawdust (and may even distinguish between coniferous and deciduous sawdust due to its calorific value), while panel manufacturers need wood chips of certain sizes that are free of contaminants. "At our place, they try to sort it so that chips, sawdust, etc., are separated," explained one participant, "then after they sort it, they decide what we will utilize and what we have to give away to someone else …. It's like a double sorting: first into each type of material, and then into what we can use in-house versus not." This two-stage sorting process highlights an important collaborative decision-making process, as companies must decide which residues have internal value and which are better passed on to external partners.

Another participant from a furniture components company described a similar practice, emphasizing the importance of separating wood by type: "We have two separate bins labelled softwood and hardwood," and a further division by particle size: "Then there's a division into shavings and sawdust. The shavings go to OSB, and the sawdust is most often used for burning to fuel our drying kiln." This phenomenon exemplifies a cascading utilization paradigm within a single facility, wherein the coarser residues are monetiaed through material recycling, specifically to produce OSB, while the finer dust is utiliaed onsite for energy purposes, contributing to the operation of wood dryers. This internal reuse can be regarded as a form of collaboration between departments within the same company, in this case the production and energy divisions, thereby reducing the need for waste disposal.

During the discussions, participants generally agreed that proper sorting is vital for adding value to biomass and facilitating collaboration. "The most important process is the selection of those waste materials, and then quick transport of them," one participant argued. By selection they meant "grouping by type of waste and directing it to the appropriate recipients." Without adequate sorting, the waste's value drops. For instance, a pellet mill would not accept mixed sawdust containing plastic or metal from construction demolition without extra cleaning. One of the problems raised was maintaining the cleanliness and purity of biomass: "often the waste is mixed … you have to then separate into fractions: larger, smaller pieces, depending on what we have a market for." This highlights the fact that technical aspects (sorting and cleaning contamination) and market aspects (demand for certain fractions) go hand in hand.

Companies either use manual labour or machinery to manage sorting, or often a combination of the two. In one focus group, a participant noted that their firm does it manually during production. "We do it by hand. As we process, we immediately separate the chips and the sawdust." Others mentioned using simple mechanized methods, such as different collection bins or conveyors, for different waste streams. Advanced sorting machines, such as screeners or separators, were not specifically mentioned; it is likely that many small and medium-sized firms rely on low-tech solutions. One challenge mentioned was that proper sorting can be labour-intensive, and many firms face labour shortages or limitations in this area. "The sorting problem also ties to the number of people at work … the volume of product isn't proportional to the number of people handling it. They complain that they have too much work and not enough people." Automation could help, but this requires investment, which will be discussed later as a challenge. In summary, effective sorting is essential in the reverse supply chain, ensuring that each type of biomass residue is used optimally and enabling firms to collaborate efficiently by exchanging well-characterized materials.

Collaborative practices

The findings of the present study indicate that a variety of distinct forms of collaboration are currently being utilized for the management of wood biomass residues. Many companies have one-to-one arrangements, such as sawmills contracting biomass companies or farmers. In these cases, the collaboration is formalized, often through a contract or regular collection schedule. One participant described such a partnership: "We have a signed cooperation with a firm that deals with all the biomass. We hand over to them the scraps left over from producing boards, floors, and beams." The partner then processes or redistributes those materials. This type of collaboration relieves the original company of the burden of processing waste, essentially outsourcing this circular task to a specialist. Such partnerships are frequently characterized by longevity and a mutual advantage, with the waste generator circumventing disposal expenses (and potentially generating revenue), while the receiving company is assured a supply of raw materials. Several participants indicated that they have stable buyers or receivers: "we have customers who produce boards from our waste;" "we have a company that picks up shavings and sawdust." This suggests the existence of a functioning secondary market for wood residues in their region. However, some noted that establishing such partnerships can be challenging for smaller or more isolated businesses. Not everyone had an easy outlet. One participant said that, for certain residues, they had to search actively for a contract to avoid waste. For example, when their sawmill received a batch of unusual wood, such as old orchard wood, they scrambled to find a buyer who could use applewood chips. This implies that information about the demand for different types of wood waste is not easily accessible; personal networks and ad hoc efforts often fill the gap.

Some larger firms incorporate downstream processes to utilize their own waste materials. A notable example was provided by a participant whose company has two divisions operating side-by-side: one producing garden wood products and the other manufacturing wood pellet fuel. "Nearly 100% of all waste from wood product manufacturing is processed into pellet," she noted. All off-cuts and sawdust from the first division go straight into the pellet plant next door. "Everything goes to pellet … it's not used for our own energy needs, it's bagged and sold for heating homes, factories," she explained. This integrated model eliminates the need for external transport and ensures a closed loop on site, as the two facilities are adjacent. Similarly, another participant from a wood panel factory said their operations are designed so that "we really don't have waste: we produce solid structural timber and also OSB, so all the shavings from solid wood production we use to make boards, and the really small waste is used in our furnaces for heating." In such cases, the "collaboration" is internal within the corporate structure (vertical integration), but it is a deliberate strategy to achieve the goals of the circular economy by co-locating processes (sometimes referred to as industrial symbiosis). Quantitative research confirms this type of activity by wood biomass companies. Over 34% of companies use it for their own needs and 27% use it for the needs of both themselves and other customers [Kawa, 2024b].

Some companies adopt a more open-market approach, selling different waste streams to the highest bidder. For example, one participant mentioned selling to "other companies" for boards or fuel depending on what the material is. Another said, "we also sell to companies that use it for either panel production or for fuel. It all depends on which waste it is." This suggests a flexible network of partners rather than a single one. For example, bark might be sold to a landscaping mulch producer, sawdust to a pellet mill and larger off-cuts to pallet or chipboard manufacturers. This approach requires maintaining relationships with multiple potential buyers and monitoring market demand and prices for each type of residue.

Participants highlighted the role of specialized service providers, such as transport companies and waste management firms, in enabling collaboration beyond direct material exchange. One focus group noted that logistics firms are part of the reverse supply chain because they transport biomass from the generation site to the reuse site. In some cases, companies hire contractors to process waste on site (for example, mobile chipping services that turn wood offcuts into wood chips on the spot before hauling them away). While participants did not describe this in detail, they implied that, without reliable logistics, even willing collaboration partners cannot exchange materials effectively. Although transport is discussed in the challenges section, it is worth noting here that logistics providers essentially bridge the gap between companies that have material and those that need it, acting as facilitators of collaboration.

Another form of collaboration that emerged from the discussions is when manufacturers take back old products for recycling. The clearest example of this was in the context of windows: "Notice that when we order windows, the company that installs them, usually the manufacturer, takes our old windows. And I think those are then subject to recovery, because from PCV windows they recover aluminium and plastic, while from wooden windows, glass and wood." In this case, the window supplier collaborates with the consumer (or construction contractor) by accepting the end-of-life product and then works with recyclers to process the components. This resembles an extended producer responsibility practice. Participants viewed this as a positive practice, although it was noted that not all sectors have such schemes. Pallets are another area. Pallet pooling companies retrieve and refurbish pallets, and a participant working in pallet production mentioned efforts to incorporate the repair and recycling of old pallets into their business model. These take-back collaborations ensure that wood is used for longer and, at the end of its life, is sorted for material recycling or energy recovery.

A close examination of the focus group discussions reveals the presence of a distinct forms of collaboration in the wood biomass supply chain. The following forms were identified: bilateral contractual cooperation between waste generators and specialized biomass users; internal collaboration through vertical integration and co-location of processes; market-based exchange with multiple downstream partners; collaboration enabled by logistics and service providers; and take-back and product return arrangements.

Value recovery practices

The ultimate goal of these collaborations is to recover value from wood biomass that would otherwise be wasted. Focus group participants provided numerous examples of how residual biomass is being used, illustrating the almost complete utilization of the material (although challenges remain). Some prevalent and innovative practices were mentioned.

Energy production is the most common form and the least circular. A large proportion of wood residues are used for bioenergy. Sawdust and shavings are often compressed into pellets or briquettes that can be used as fuel in heating systems. Some companies produce pellets internally for sale, while others sell sawdust to external pellet producers. One participant clarified to the moderator that when they say a residue is used for "fuel, then pellet is produced" from it. Another participant observed that biomass is also used directly for heat in the industry: "we use wood waste to fire the furnace in the wood-drying kiln." In regions aiming to replace coal with renewable fuels, wood pellets have become important, so collaboration between the wood and energy sectors is a major driver. Participants felt that this trend would grow: "we have a coal crisis now… in the next 10–20 years we'll have mostly to transition to renewable energy, so biomass will definitely gain importance." They even mentioned energy crops (such as fast-growing willows) in passing, although these are outside the remit of the wood industry. In summary, converting residual biomass into energy through pelletization, briquetting or direct combustion in power stations is the easiest way to reuse wood, and relies on supply chain linkages between wood processors and energy producers or markets.

Many participants mentioned that wood chips, sawdust, and ground wood waste are used to make composite materials such as particleboard, fibreboard, and OSB. For example, one sawmill worker said their wood chips go to "OSB boards." Another participant said that their company recycles all solid wood offcuts internally into glued laminated boards and OSB, indicating direct integration of residue into new products. There was broad awareness that "if you glue these small wood pieces with resins, you can make new panels," and that finer particles actually make better panels (since large chunks would be problematic in a smooth board). This practice is underpinned by the principle of cascading use, which asserts that solid wood is utilized for its inherent value as lumber, while any residual material that cannot be sold in this capacity is repurposed as feedstock for the production of panels. It was also noted that furniture manufacturers might use reclaimed wood or chipboard made from recycled wood. One participant explicitly listed the paper industry as all being involved in taking wood residuals. The paper and pulp industry is a notable collaborator, as it can use clean wood chips or sawdust to produce paper or cellulose derivatives. Indeed, a focus group member mentioned, "I think such chips and sawdust can be given to make paper, cellulose, because that's one of the ingredients." Another added that some companies even ferment sawdust to produce ethanol (for fuel additives), indicating a chemical processing route. "I know the company we give sawdust to also produces ethanol from it, via fermentation." This innovative valorization process involves converting wood sugars into biofuel, creating a circular strategy that links to the biofuel industry.

Participants often mentioned that bark and low-grade wood residues are used in agriculture and gardening. "Bark is used for gardening and similar things," said one participant of their biomass contractor's usage. Bark and wood chips are common landscaping mulching materials and are sold in gardening stores. Another participant noted that certain companies specialize in processing pine needles and bark into a material that acidifies soil. "They process needles or bark into a component that is added to soil sold in stores… used in horticulture… basically a compost." This example illustrates a cross-sector linkage, in which wood waste is converted into a horticultural product. Similarly, wood shavings and sawdust can be used as animal bedding (e.g. in horse stables or on poultry farms) and eventually composted. One participant explicitly added "the agricultural sector – tree bark can be used as bedding for animals" to the list of actors in the reverse supply chain. While these uses may not always be high-value in monetary terms, they are important for ensuring that nothing goes to waste, and they facilitate collaboration between wood processors and agricultural communities. Some participants also associated biomass with natural fertiliser, for example using sawdust, straw or wood chips to produce compost or mulch. One participant gave the colourful analogy of a nutrient cycle: "like cows eat grass and excrete, which fertilizes the grass again. It all goes in a circle".

In addition to processing wood into new materials or energy, the groups also discussed the direct reuse of wooden components, which is another aspect of the circular economy. In construction and crafts, old wood can sometimes be repurposed directly. Participants provided a number of examples illustrating this process. Old boards from buildings, if in good condition, are reclaimed and refurbished by sanding and re-impregnating them, and then sold as vintage or rustic material. Old wooden doors can be repainted and reused or even turned into decorative frames. Pallets are repaired and reused multiple times. One participant described how even demolition waste, such as roof timbers, can be salvaged: "old roof battens and beams can be reused to build a new roof if they're in good shape, saving some cost." However, it was noted that inspection is only possible following cleaning and removal of damaged components, in order to ensure structural integrity. Another participant mentioned a niche practice: making household items out of reclaimed wood, such as "stools or shelves from old boards", and artists using tree roots or stumps to create furniture or art pieces. While these reuse practices are more ad hoc and not large-scale industrial processes, they represent a cultural shift in viewing "waste" wood as having potential value. They can also spawn small businesses or local collaborations, for example between demolition contractors and reclaimed wood sellers, or individuals exchanging materials.

Overall, the discussions conveyed a strong message that "everything can be used for something" in the wood biomass domain. Participants often expressed the view that "you can work something out" from anything, whether by reusing, remanufacturing, or recycling. While this reflects optimism and creativity among industry practitioners, it also comes with the caveat that making full use of everything requires overcoming certain practical challenges, which we will explore next.

The analysis revealed several main pathways of value recovery from residual wood biomass: energy recovery through pelletization, briquetting, and direct combustion, material recycling into panels, composites and paper products, agricultural and horticultural applications, and direct reuse and remanufacturing of wooden components.

Barriers and opportunities in collaboration

In the present study, the factors that hinder or facilitate cooperation in the wood biomass supply chain were examined. A notable challenge that was mentioned was the degree of fragmentation and engagement issues. One participant made the telling comment: "as the producer of the material, what the end receiver does with it is not really our business, let him pay the invoice," implying a hands-off attitude once the waste is sold. This situation is indicative of a conventional linear perspective, in which the company is content to transfer the waste without concern for its ultimate destination, provided that the financial compensation is received. While this attitude is practical, it may prevent deeper collaboration, such as working together to improve material quality for reuse or investing jointly in equipment. It suggests that economic transactions define relationships and that environmental or strategic collaboration is secondary.

Another barrier is when the economic conditions do not support collaboration. If neither the generator nor potential partners are willing to pay for the disposal of certain waste, a collaborative solution may be unattainable. As mentioned earlier, partnerships can fall apart if transport or processing costs render a material non-viable. One participant lamented that "some things just aren't worth anyone's time. You can't find a taker unless you pay them, because they won't do it for free," citing very low-grade waste and remote locations as examples. This suggests the need for economic incentives to encourage collaboration on harder-to-recycle materials.

Despite these issues, participants recognized that improving collaboration was key to strengthening the circular supply chain. Several ideas emerged. Many felt that systems could be developed to connect waste generators with potential users more efficiently. Whether through industry associations or digital platforms, facilitating the exchange of wood residue was viewed positively. One group discussed the concept of a central marketplace or database for wood waste, which would enable a small cabinet maker with surplus sawdust, for example, to find a local farmer in need of animal bedding or a recycler to post demand for certain feedstock. While this is not currently formalized in their region, some participants were aware of informal social media or web groups where such exchanges already take place.

There was interest in collaborative logistics solutions, such as sharing transport for waste among companies in the same area, in order to achieve economies of scale and reduce costs. For example, if multiple small workshops pooled their waste and sent it to a recycler in one truck, which could overcome the cost barrier. One participant noted that sometimes they already do "coordinating trips to deliver products and back-haul waste." Such practices could be expanded through cooperation.

Some participants touched on the idea of vertical integration, such as contracts that close the loop. For example, a panel board company could collaborate with furniture manufacturers to sell them boards and take back their offcuts to produce new boards. One person mentioned that producers can indeed become receivers, giving the example of window companies taking back old windows, and suggested that this model could be replicated elsewhere. Such "closed-loop" contracts could ensure a continuous flow of materials.

Mentioning municipal waste centres and green waste suggests the potential for industries and local governments to collaborate more formally. Participants saw this as largely untapped. If cities implemented better wood sorting and liaised directly with wood recyclers, more post-consumer wood, such as bulky furniture waste, could be diverted to the industry. One participant noted that regulatory support could encourage or enforce such links, for example by requiring construction and demolition contractors to send wood debris to recycling facilities rather than landfill. This would stimulate collaboration with those facilities.

Essentially, while the current collaboration model relies on bilateral agreements and ad hoc networks, the focus groups identified clear ways to strengthen the supply chain through better communication, shared logistics and potentially formalized exchange systems. The willingness was there. "The opportunity is 100% utilization of the raw material" said one participant, implying that if everyone in the chain works together, theoretically all wood can find a use. However, achieving this would require the separate pieces to be woven together into a more cohesive loop.

Many participants identified a significant opportunity within the broader energy context. With fossil fuels (especially coal) in decline due to climate policies and supply issues, biomass fuels such as wood pellets are set to become increasingly important. "We have a coal crisis… there's a big chance that all these things we're talking about will sell better," the moderator posited, to general agreement. However, one participant cautioned that people mistakenly believe wood is a free resource: "everyone thinks they can just go to the forest and collect wood. It's not that simple," but he did concede "it is a chance." The implication is that as carbon emission pressures rise, industries and heating sectors will look for renewable alternatives, and wood biomass (being renewable) has a role: "biomass is definitely renewable," as one noted. This could drive investments in biomass boilers, pellet manufacturing capacity, and improvements to the supply chain. However, to seize this opportunity, sustainability must be ensured (i.e. not over-harvesting for energy and using true waste streams). The participants touched on the importance of planting more to replace what is used, linking opportunity with responsibility.

During the discussion, it was suggested that changes to taxation or subsidies could encourage the reuse of biomass. One such idea is to lower VAT on recycled wood products or biomass fuels. If governments were to incentivize businesses financially to use recycled materials (through tax credits or grants for circular economy initiatives), companies would be more willing to collaborate. Participants also hinted at the role of consumer choices: "Lowering the price of eco-friendly products would encourage a wider group of customers, which would reduce people's choice of plastic," said one participant. This indicates an opportunity in marketing and consumer awareness. If end consumers prefer products incorporating recycled wood or that are recyclable themselves, this creates demand for companies to collaborate in producing such items. Demand for furniture made from reclaimed wood or biodegradable packaging made from compressed biomass, for instance, can stimulate new partnerships with suppliers of these materials. Examples mentioned included wood-based single-use dishes and wooden cutlery, which point to emerging product markets that did not exist a decade ago. Focus group participants seemed aware of these trends, mentioning seeing wooden or biomass-based cups and plates. As such products become more popular, cross-sector collaboration between the wood industry and consumer goods manufacturers will become more extensive.

Participants referenced technology as an opportunity. Innovation could make biomass utilization easier and more cost-effective. For instance, improved drying and storage technology could solve the moisture issue, while advanced sorting systems (e.g. AI-powered) could reduce labour requirements. Furthermore, modular bio-refineries could convert efficiently mixed wood waste into chemicals or fuels. One participant noted hearing about processes to make "ethanol from sawdust," which is an emerging technology (cellulosic bioethanol). Another participant mentioned "biocoal and bio-oils" from wood, referring to pyrolysis or hydrothermal processes. While these were just brief mentions, they demonstrate that some industry players are exploring technology for uses beyond the traditional. As these technologies become commercially viable, new avenues for collaboration will open up. For example, a chemical company might partner with sawmills to source feedstock for bio-oil production.

Another opportunity lies in engaging with sectors that have been mentioned but are perhaps not deeply involved yet, such as the municipal waste management system. Participants noted that landfills and waste collection points are already sending wood to recyclers. Boosting circular outcomes would be as easy as making sure that all civic amenity sites are required to sort out clean wood waste and then direct it to wood recyclers instead of burning it or dumping it in the local landfill site. This would require coordination between local governments, waste companies, and the wood industry. Policymakers could mandate or facilitate such practices, for example by banning untreated wood from landfills or creating subsidies for businesses that use recovered wood from municipal waste. Participants seemed optimistic that "special containers for bulky waste" and similar measures are already in place, but there is likely room to expand these programmes.

The barriers and opportunities identified in the focus group discussions are largely consistent with previous research on circular and reverse supply chains, while also revealing several context-specific insights. It has been widely established in the extant literature that economic and logistics constraints, particularly transport costs and scale inefficiencies, represent significant obstacles to the utilization of circular biomass [Khan et al., 2024; Prahinski, Kocabasoglu, 2006]. The present findings corroborate these challenges at the operational level, emphasizing how distance, fragmentation of waste streams and limited volumes impede collaboration, particularly for small and medium-sized enterprises. Moreover, issues pertaining to the fragmentation of responsibilities and the paucity of engagement between relevant parties have been shown to resonate with the findings of preceding studies, which have underscored the pivotal function of coordination, trust and the exchange of information in facilitating circular flows [Alam et al., 2025; Parsa et al., 2021]. However, this study extends existing knowledge by illustrating how such coordination problems manifest in everyday practices, where waste is often transferred with minimal concern for downstream utilization, provided that immediate economic transactions are satisfied. Concurrently, the opportunities identified by practitioners correspond with emergent themes in the circular bioeconomy literature, including shared logistics solutions, industrial symbiosis, and the mounting demand for biomass-based energy and products [Jarre et al., 2020; Sherwood, 2020]. The results of the focus group discussions highlight that these opportunities are not solely technological in nature. Instead, they are contingent on organizational arrangements, policy incentives, and the existence of platforms that enable cross-sector collaboration.

Summary

Theoretical implications

This study makes a contribution to the existing literature on the circular economy and circular supply chain management by providing insights into collaboration within the wood biomass supply chain that are grounded in empirical evidence. The findings demonstrate that the phenomenon of circularity in practice is not solely the result of formal, strategically designed partnerships, but often emerges organically through a dense network of formal and informal relationships among diverse actors. The observed interconnections between sawmills, wood product manufacturers, pellet producers, recyclers, and even municipal organisations highlight the importance of interdependence as a foundational principle of circular supply chains.

By documenting how residual biomass flows across organizational boundaries, the study reinforces and extends existing theories of industrial symbiosis and reverse supply chains. The evidence suggests that collaboration is already embedded in everyday operational practices, even if this is not always conceptualized as a "circular economy" by practitioners. Concurrently, the findings underscore that economic, logistic, and quality-related barriers which are frequently identified in the reverse supply chain literature remain highly pertinent in the context of wood biomass. Significantly, this study introduces a more nuanced perspective by underscoring the pivotal role of policy and market conditions (e.g. energy prices, inadequate incentives for green products) in shaping the feasibility and extent of collaboration.

The findings of this study indicate that transitions towards circular supply chains should be conceptualized as evolutionary and relational processes, rather than as purely technology--driven or top-down policy interventions.

Managerial implications

From a managerial perspective, the results indicate several actionable steps for companies operating in the wood sector. Firstly, it is incumbent upon firms to conduct systematic audits of their waste and by-product streams. The identification of the type, volume, and current disposal method of each residue has the potential to reveal hitherto untapped economic potential, thereby transforming waste streams that generate costs into sources of revenue. A significant proportion of the participants' experiences demonstrate that even rudimentary classification practices have the capacity to engender novel concepts for valorization.

Secondly, it is incumbent upon managers to explore proactively collaborative investment models. The formation of joint ventures, cooperatives, or consortia can facilitate shared investments in processing technologies that would otherwise be financially unfeasible for individual firms. In a similar vein, the implementation of industrial symbiosis and co-location strategies, such as the aggregation of sawmills, furniture producers, panel manufacturers, and biomass energy facilities, has been demonstrated to result in substantial reductions in logistics costs and enhancements in material efficiency.

Thirdly, the study emphasizes the strategic significance of information sharing and networking. It is imperative that managers engage not only within the traditional boundaries of the wood industry, but also across sectors, including energy, chemicals, agriculture, and municipal waste management. The expansion of communication channels and participation in industry platforms has been demonstrated to facilitate the identification of novel applications for residual materials by firms, as well as the establishment of relationships with non-obvious partners. In this sense, collaboration can be regarded as both a social and informational challenge as well as a technical one.

Limitations and future research

While the study provides valuable insights, it is important to acknowledge several limitations. The findings are based on three focus group interviews with practitioners from the Polish wood sector, reflecting a specific regulatory, economic, and market context at a particular point in time. Consequently, the transferability of the conclusions to other regions or countries may be constrained. It is acknowledged that diverse institutional settings may encounter a range of distinct barriers, or alternatively, may already have more advanced collaborative arrangements in place.

Future research could address these limitations in several ways. The execution of comparative studies across countries or regions would facilitate the identification of how contextual factors influence collaboration and circularity in wood biomass supply chains. Moreover, the expansion of the range of stakeholders to encompass policymakers, logistics providers, and other intermediaries would facilitate a more comprehensive perspective on the system. Finally, it is imperative to investigate the end-user or consumer perspective, particularly demand for products containing recycled wood or biomass. This will provide valuable insights into market-side drivers and inform strategies to strengthen circular economy outcomes.

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